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# **Detecting Japan Tsunami Marine Debris at Sea: A Synthesis of Efforts and Lessons Learned**

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## Executive Summary

This report synthesizes actions and lessons learned by the National Oceanic and Atmospheric Administration (NOAA) and the overall marine debris community through efforts to detect marine debris caused by the tsunami that struck Japan in March 2011. This tsunami inundated over 217 square miles of coastal Japan and washed an estimated 5 million tons of debris out to sea as it receded. The Japanese government estimated that 70 percent of that total sank immediately, leaving 1.5 million tons of Japan tsunami marine debris (JTMD) that broke up and dispersed over the North Pacific in the months and years following the tsunami.

Following the tsunami, the marine debris community – including U.S. federal, state, and local agencies as well as academic and non-governmental groups – began efforts to assess the quantity, location and movement of the remaining JTMD in order to better anticipate and prepare for its potential impact on marine and coastal resources and communities. While shorelines throughout the Pacific are consistently impacted by chronic marine debris, the acute pulse nature of the release of JTMD combined with the potential for additional impacts - such as navigational hazard from large objects and vessels and invasive species impacts from objects colonized by species native to Japan - created specific interest in and concerns with JTMD.

Because of the very large area where debris was expected to disperse, detection was paired with modeling efforts in order to focus detection resources on areas where debris was most likely to be located. The characteristics and behavior of any debris object is important in order to better understand and model its movement, durability/persistence, and where it is likely to collect in the ocean or on shore. Understanding the characteristics of the debris is also important in identifying the target “profile” that the debris will present to a sensor, in terms of surface area, composition, color, and other attributes. With more specific and accurate information on the behavior of debris, the capability and accuracy of models that predict debris concentration based on oceanographic features and forcing can be increased. These modeling outputs can also aid in focusing direct detection efforts on areas that are more likely to hold higher densities of debris.

Direct detection efforts were divided between targeted detection efforts - where the primary goal of the mission or activity was focused on marine debris - and opportunistic and voluntary efforts - where debris reporting was secondary to the primary mission or activity. These efforts, whether targeted or opportunistic, involved visual and remote sensing from multiple platforms, including vessels, aircraft, satellites, and shorelines.

Targeted detection activities primarily utilized satellite and aerial assets for remote sensing and shoreline monitoring programs for direct shoreline data collection. Prior to the JTMD event, satellite data had not been used extensively for debris detection by NOAA or its partners. Through an extensive effort led by NOAA’s National Environmental Satellite, Data, and Information Service (NESDIS), different satellite sensors, acquisition approaches, and analysis techniques were implemented and tested over the course of the response. While available commercial satellite data proved to have limited capability in detecting individual debris objects, it provided valuable intelligence in confirming that there were no large masses or “islands” of tsunami debris, which was a longstanding public concern.

Aerial operations in the open ocean were primarily limited to opportunistic reporting by partner agencies during the execution of their primary missions. Shoreline aerial surveys were very successful, however, in showing areas of high debris concentration and providing information to guide cleanup prioritization decisions in areas where surveys occurred.

Opportunistic sightings were a primary source of information throughout the response, with over 1,900 debris sightings reports coming to the NOAA [disasterdebris@noaa.gov](mailto:disasterdebris@noaa.gov) reporting and tracking system. Of these, the majority of debris sightings came from vessels (637 to date) and shore-based observations (1,270 to date), while fewer were from aircraft (12 to date) and satellite (0 to date).

Across the varying detection efforts, a consistent set of lessons-learned and opportunities emerged:

- **Interest translating to advancement** - the acute and specific nature of JTMD and the associated human tragedy led to a higher level of interest in the overall marine debris issue, both from the public and from agencies and organizations that participated in response activities, including detection. This provided an opportunity to advance the state of knowledge on debris detection, modeling, and monitoring as it applies to not only JTMD, but to future acute debris events, and chronic background debris.
- **Limitations in dedicated resources** – For high demand or high cost assets, such as vessels or aircraft, getting access to dedicated time for debris operations is challenging, especially in the very remote areas of the North Pacific. Finding ways to partner and integrate debris detection operations with existing missions in advance of acute debris events could help address this need.
- **Satellite detection capabilities** – Satellite detection offers key capabilities in being able to provide increasingly high resolution (down to 0.5 m) imagery in areas that are otherwise practically inaccessible. However, the combination of diverse debris types spread over a wide area makes successful identification of individual debris objects by satellite very challenging. Additionally, there is an inherent tradeoff between coverage area and resolution: as resolution increases, the coverage area decreases. This can result in a narrow “soda-straw” look at individual target areas. Furthermore, even at high resolution, it remains difficult to firmly identify anomalies or objects that are detected as debris. Despite these challenges, significant progress was made in understanding the best sensors and analysis techniques to detect debris, and satellite data did provide key value in confirming that debris was widely dispersed, and not matted in islands or rafts, which was a public concern. In future events, having consistent satellite data collection to track debris as it breaks up can help provide clear intelligence on debris movement and also on thresholds for detection.
- **Standardization and/or expansion of opportunistic reporting** – Adding the capacity and/or requirement for vessels/observers to report the overall track of the vessel/aircraft and where they did not see any debris could significantly benefit modeling and the overall base of knowledge on debris location and concentration. Also, integrating common guidance or protocols for the specific information to be captured, the terminology used, and data collection structure employed could increase the compatibility and ease of data sharing between reporting systems (NOAA, states, etc.). This, in turn, could help improve the feedback to users (public, science, response) and help make information more broadly accessible and applicable during a response.

Taken together, the results of detection activities focused on JTMD have advanced the state of knowledge on detection of debris at-sea and will help inform future detection activities, both for chronic marine debris and for responses to events that create an acute release of marine debris (tsunamis, hurricane or storm events, vessel releases, etc.).

## Acronyms and Abbreviations

CONOPS	Concept of operations
DEC	Alaska Department of Environmental Conservation
DFG	Derelict Fishing Gear
DOD	Department of Defense
FLIR	Forward Looking Infrared
ft	Feet
GNOME	General NOAA Operational Modeling Environment
HAZMAT	Hazardous material
HF	High frequency
ICC	International Coastal Cleanup
ICR	Information Collection Request
JTMD	Japan Tsunami Marine Debris
LiDAR	Light Detection and Ranging
m	Meter
MARAD	U.S. Department of Transportation's Maritime Administration
NGA	National Geospatial-Intelligence Agency
nm	Nautical mile
NOAA	National Oceanic and Atmospheric Administration
NOAA MDP	NOAA Marine Debris Program
NOAA NESDIS	NOAA National, Environmental, Satellite, Data, and Information Service
OMB	Office of Management and Budget
PRA	Paperwork Reduction Act
RGB	Red-green-blue
SAR	Synthetic Aperture Radar
SCUBA	Self-contained underwater breathing apparatus
UAS	Unmanned Aircraft System
USCG	U.S. Coast Guard

## 1.0 Introduction

Marine debris is an ongoing problem with everyday impacts. While much of the marine debris in the world's oceans comes from chronic introduction through land and ocean-based sources as the result of human behaviors and choices, acute events including natural disasters contribute to the marine debris problem. Examples of this include Hurricanes Katrina and Rita in the Gulf of Mexico, the American Samoa tsunami of 2009, and the Tōhoku earthquake and tsunami of 2011 that is the focus of this report.

The earthquake and tsunami that devastated Japan in March 2011 was a human tragedy – the disaster claimed nearly 16,000 human lives, injured more than 6,000 people, and destroyed or damaged countless buildings. As the wave retreated, it carried with it significant amounts of debris back into the ocean. The Government of Japan (GOJ) estimated that roughly 5 million tons of debris were washed to sea, of which roughly 70 percent sank, leaving an estimated 1.5 million tons of floating debris to spread over the Pacific Ocean, moving and dispersing based on wind and currents in the North Pacific. The GOJ also estimated that debris continued to sink and weather over time, further reducing the total quantity of floating debris under the 1.5 million ton estimate. In the days following the tsunami, multiple organizations and agencies noted the presence of this debris immediately in operational reports from the disaster response. While the primary efforts focused on immediate disaster recovery, during this initial response period NOAA and other groups began to opportunistically collect observations (photos and anecdotal reports, primarily) on debris locations and types in order to better understand the scope of the debris introduction caused by the tsunami. Initial reports and images described a wide range of debris by size, shape, and composition, with individual images showing vessels of various sizes, structural debris, fishing gear (lines, buoys), and a wide variety of household objects.

Satellite imagery and aerial photos immediately following the disaster captured images of buoyant materials forming large debris fields or patches in the water near Japan's coast. However, these fields were no longer visible by mid-April 2011, as the debris had dispersed based on differences in the composition and shape of the objects and the resulting speed and direction of winds and ocean currents that drove them across the ocean. In the months following the tsunami event, multiple groups began working to both model the movement and fate of the debris and to use targeted and opportunistic detection approaches to locate and estimate the quantity and type of debris remaining in order to better understand, assess, prepare for its potential arrival and any resulting impact. These efforts are the focus of this report.

The fastest moving, highest floating of the remaining debris began arriving on the West Coast of North America starting in the winter of 2011-2012, with later arrivals in Hawai'i. This JTMD continues to arrive through the publication of this report. NOAA expects scattered tsunami-related debris to continue to arrive on U.S. and Canadian shores intermittently over the next several years, eventually blending into the overall pre-existing marine debris problem in the Pacific.

NOAA and other responding agencies have found that the majority marine debris generated from the Japan tsunami has been difficult to distinguish from the "typical" marine debris that washes up on shorelines every day, because tracing any one object back to its source with certainty is rarely possible. In the three years since the tsunami, NOAA has received more than 1,900 reports of debris to date from at-sea vessels and beachgoers in Pacific-area states and British Columbia. However, as of the time of this

writing, less than 60 objects have been confirmed as JTMD. “Confirmed” tsunami debris are objects that can be conclusively traced back to the disaster, based on a clear fingerprint such as a government registration or personal information that is confirmed through the GOJ. Examples of these objects include vessels, large docks that arrived in Washington and Oregon, and personal objects such as sports balls that have ownership information written on them. NOAA works closely with the GOJ and its Consulates to confirm whether reported debris objects originated from the tsunami impact zone. The confirmation status of debris objects was a valuable input early in the response because the presence of confirmed sightings showed definitively that tsunami debris had reached U.S. shorelines. However, not all of what arrived was reported or could be confirmed, and there are undoubtedly tsunami-related objects on U.S. shorelines that cannot be confirmed. Therefore, while this report focuses on detection of JTMD, everyday marine debris detection is also included by default, because debris is first detected and then evaluated for potential confirmation as JTMD.

Ideally, detection of debris, either at-sea or on shore, is followed by immediate removal of the debris in order to prevent further threat or impact. However, there is no established response fund to specifically address response to, or removal of, disaster-related debris, and funds available for cleanup of chronic, everyday marine debris are already a limiting factor in cleanup activities. The method and funding for large debris removal is most often assessed and identified on a case-by-case basis by management agencies and officials at the federal, state, local and tribal levels.

While this report presents JTMD detection activities and the lessons-learned from their design and application during the overall JTMD response, many of the structures or approaches remain in place, either actively collecting data, or available for reactivation as needed, either as part of the JTMD response, or for response to future events.



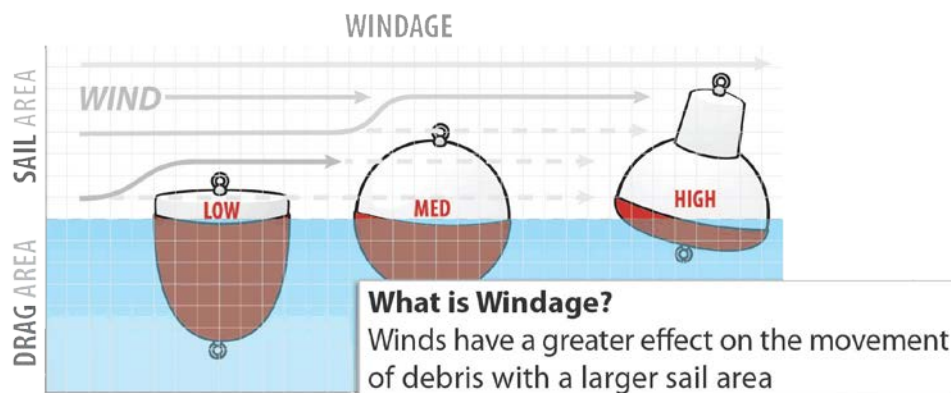
## 2.0 Detection Approach Elements

As stated, the primary goal of JTMD detection efforts was to gather information on the quantity, composition, and movement of floating debris in order to assess and prepare for the potential impact it might cause. While there had been multiple projects previously executed by the marine debris community focused on either targeted or opportunistic at-sea detection, the broad diversity of the debris types and scale of the target area for JTMD meant that a more holistic approach would be necessary.

In order to maximize the coverage and likelihood of success for any detection effort that was undertaken, it was important to build a combined detection approach that integrated information on the behavior of debris to model its movement, and then use those estimates to focus targeted debris detection efforts and inform requests for opportunistic reporting of debris sightings. These elements are briefly described below.

### 2.1 Characteristics and Behavior of JTMD

Understanding the characteristics and behavior of JTMD at-sea is fundamental to developing and selecting the most appropriate modeling and detection approach. Modeling the movement and concentration of a range of debris requires an understanding of how that debris will move, degrade, or change over time, referred to here as the overall “behavior” of the debris object. The behavior is dependent on the size, weight, buoyancy, and degradation timeline of the debris, which varies significantly. As an example, an uncoated foam buoy may move differently (in speed and direction) and degrade more quickly than an overturned skiff, both of which are examples of confirmed JTMD objects. A key component of this variability is driven by the “windage” of an object. This variable, which is reflected as a percentage of the wind force, captures the relative influence of wind on a floating object’s downwind speed based on the sail area above water relative to the drag created by the area of the submerged portion (Figure 1). As an example, a high-floating, high-windage object such as a buoy that would be influenced heavily by wind could have a windage value of 5 percent. Conversely, a derelict fishing net, which would float below the surface and be primarily influenced by currents, would have a windage value close to 0 percent.



**Figure 1 – Debris Windage.** The speed and direction of a debris objects movement is influenced by its windage. “Windage” or “leeway” is a measure of the relative influence of wind on an object based on the combination and interaction of how much sail area (surface area above the water’s surface) versus the drag area (area under the water’s surface).

Detecting those marine debris objects through remote sensing requires an understanding of the properties of the debris that determine the target profile it presents to sensors and to the analysts who process the data those sensors return. This target profile is influenced by a combination of the object's color, composition, size, degree of bio-fouling, and other features. As an example, small or broken-up white foam buoys may be difficult to distinguish from sea-surface features (waves, sea-foam) to an analyst, but they may have a different spectral signature than the naturally occurring background. Likewise, an overturned skiff coated in barnacles may not return the same spectral or visual signature as an upright, clean skiff might typically. Understanding the likely target profiles allows for a higher probability of detection of debris.

While there have been isolated sightings of large objects, such as large vessels and docks, sightings and confirmed objects indicate that the majority of JTMD is similar to typical marine debris. That is, the majority of the debris objects are likely to be relatively small in size (less than 2-3 square meters), with variability in all other characteristics and properties.

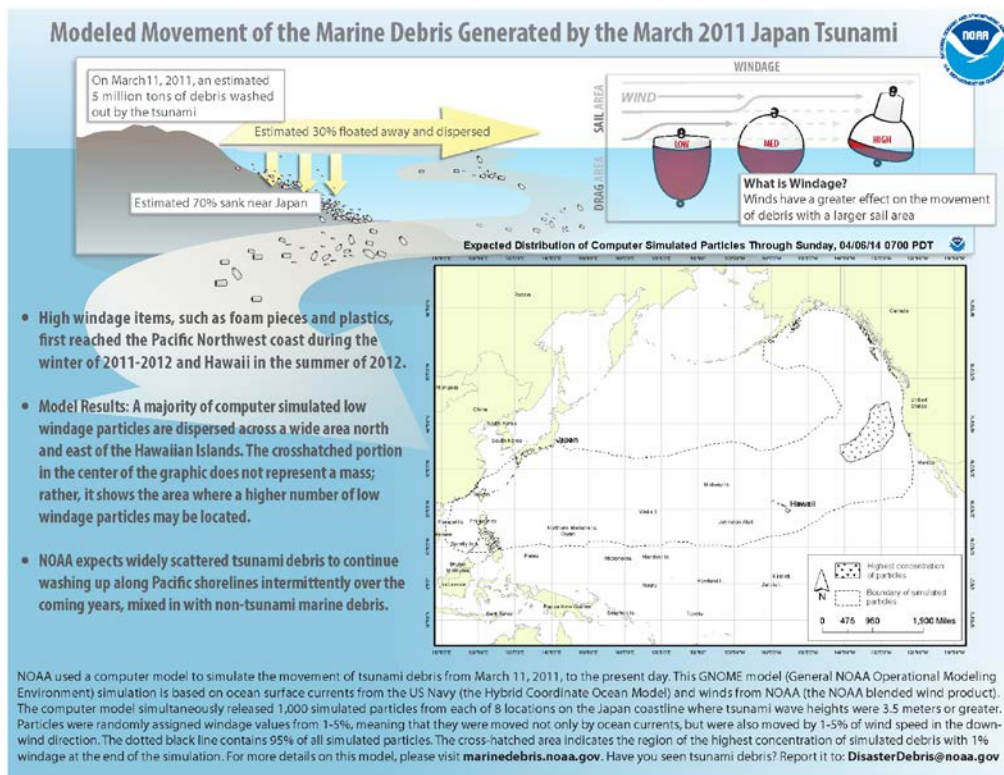
## **2.2 Modeling JTMD Movement and Concentration**

Given the enormity of the area of the North Pacific that JTMD was likely to transit, which measures millions of square kilometers, it was important to find ways to focus the limited debris detection resources on areas of potential elevated JTMD presence or concentration.

Multiple government and academic groups began efforts to model the fate and movement of JTMD in the months after the tsunami. While early satellite imagery and opportunistic reports from vessels gave limited indication of debris types and potential behavior profiles, as time passed from the event, the lack of sightings and detection data meant there was limited information from which to construct model parameters. NOAA researchers have worked with the GNOME (General NOAA Operational Modeling Environment) hindcast computer models to estimate the movement and resulting spread of JTMD since the tsunami event (Figure 1). In the GNOME modeling run for JTMD, 8,000 simulated debris particles were released from locations on the Japanese coastline where the tsunami wave height was measured at 3.5 m or higher. In order to simulate the wide diversity in the objects washed to sea by the tsunami, each particle was assigned a random windage from 0-5 percent (simulating a variety of items such as a fully submerged fishing net moving solely with currents up to an inflatable life-raft driven primarily by winds). The movement of these simulated objects, or particles, was then modeled using archived satellite-derived measurements of currents and winds up to the time of the run, providing a picture of the overall movement and dispersion of the debris up to that point in time. This type of model output is called a "hindcast" because the model uses actual wind and current data to simulate and estimate the present location and distribution of debris and its path up that point, rather than using either short-term forecast data or long-term historical average data to show where debris might go in the future. The initial runs of this modeling effort conducted in early 2012 showed the fastest moving and most buoyant simulated debris items reaching the Pacific Northwest coast during the winter 2011–2012, with later arrivals of lower-windage debris, mixed in with both chronic debris and higher windage JTMD objects that had not already been driven ashore.

This modeling output also showed areas of higher concentration for at-sea JTMD, generally in the North Pacific to the north of Hawai'i. Coupled with modeling outputs from other active groups, including the University of Hawai'i International Pacific Research Center and a team led by the Government of Japan

Ministry of the Environment, these efforts provided parameters to focus targeted detection activities over the course of the overall JTMD response.



**Figure 2 – Debris Modeling.** NOAA has used a computer model to simulate movement of tsunami debris from March 11, 2011, to the day of the model run. These model runs are termed “hindcasts,” because they use retrospective satellite-derived wind and current information to estimate where debris has been based on actual data rather than where debris might go in the future based on forecasted conditions. This GNOME simulation is based on ocean surface currents from the U.S. Navy (the Hybrid Coordinate Ocean Model) and winds from NOAA (the NOAA blended wind product).

## 2.3 Direct Detection of JTMD

Direct detection efforts, defined as targeted or opportunistic efforts to identify and record specific debris presence and quantity, began immediately after the tsunami with requests to responding agencies for imagery and reporting of debris sightings. Many of the initial images and reports came from the U.S. Navy and other military organizations responding to the humanitarian disaster, as well as the international satellite analysis community. However, as the immediate disaster response and nearshore maritime presence declined and the debris dispersed offshore, reports declined as well. Following that draw down, partners worked to identify potential opportunities for detection or tracking of JTMD in the Eastern Pacific area, where much of the JTMD was expected to head. Throughout the summer and fall of 2011, opportunistic reports of potential JTMD from ship-based observations were the primary source of information, and included two reports of confirmed JTMD to the north and west of Hawai‘i.

Starting in late 2011, NOAA began to work with multiple partners to identify opportunities for targeted detection using remote sensing assets deployed from aircraft or satellite platforms.

## 2.4 Sensor Types

Successfully identifying the appropriate approach for direct detection of marine debris requires an understanding of the characteristics and behavior of the marine debris, and the resulting profile or target they can be expected to present to the sensor. Sensors can range in complexity from the simple visual imagery to hyperspectral sensors. For the detection of floating debris, it is important to consider a sensor's resolution, the availability of coverage in the area of interest, and the method of analysis to initially detect and eventually identify the debris object or objects in the data the sensor returns. A sensor with 1 m resolution may be more likely to detect smaller debris or smaller debris collections than the same sensor type with 30m resolution. Some sensors, particularly satellite-based sensors, may only cover portions of an area-of-interest or may only cover an area at specific times or during specific seasons. Furthermore, it's important to understand what a given sensor is actually detecting (e.g. radar signature, multispectral return, panchromatic visual image, etc.), as some may be better at detecting debris under different conditions.

Platforms to deploy these sensors can range from surface (e.g., ship), to aerial (e.g., aircraft, unmanned aircraft systems [UAS]) to space (e.g., satellite). Table 1 provides a short description of sensors that may be used for direct detection of marine debris, including typical platform pairings, relative cost, and whether debris data exist.

Additionally, an important distinction must be made between a sensor's ability to *detect* an object or anomaly, and the ability to positively *identify* that object or anomaly. As an example, a large white foam buoy that is roughly 1 m wide by 2 m long would show as two white pixels in a 1 m resolution satellite image. While it may be possible to notice or *detect* the presence of the buoy as an anomaly or potential object, it will be very difficult from those two pixels to positively *identify* the buoy or distinguish it definitively from naturally occurring phenomenon, such as breaking wave crests. This general distinction, and challenge, is true across most sensors, but especially impactful in cases where target objects are at the very limit of a sensor's resolution.

**Table 1 – Sensors for At-Sea Detection of Marine Debris.**

*Sensors potentially applicable for marine debris detection including platforms, relative cost, and known uses. Passive sensors rely on the light or energy reflected back to the sensor off of the object, while active sensors emit energy and measure variances in the returned energy. Sensors with an existing data set have been used for debris detection or other similar application previously.*

Sensor Type	Class	Description	Platform Pairing		Existing Data Set	Cost	Used For	
			Aerial	Satellite			JTMD	General Debris
<b>RGB Video</b>	Passive	Typical red-green-blue (RGB) video sensor, as found in common cameras	✓		Yes	Low	Yes	Yes
<b>Digital Camera</b>	Passive	High-resolution still camera	✓	✓	Yes	Low	Yes	Yes
<b>Infrared Camera</b>	Passive	Thermal cameras that capture images of heat radiated from objects	✓		Limited	Medium	Yes	Yes
<b>Hyperspectral</b>	Passive	Cameras that generate images with more spectral information (approximately 30 times as much) than the three spectral bands of RGB. The data comprise a three-dimensional array with two spatial and one spectral dimension.	✓	✓	No	High	Unknown	Yes
<b>Multispectral</b>	Passive	Intermediate between three color RGB cameras and hyperspectral imagers and most commonly used from satellite.		✓	No	Medium	Yes	Yes
<b>Radar</b>	Active	A detection system that works by sending out pulses of high-frequency electromagnetic waves that are reflected off the object back to the source.	✓		No	High	No	No
<b>Light detection and ranging (LiDAR)</b>	Active	A detection system that works on the principle of radar but uses light instead of a radio signal.	✓		Yes	High	No	Yes
<b>Synthetic aperture radar (SAR)</b>	Active	SAR works by collecting the echo returns from many radar pulses and processing them into a single radar image.	✓	✓	Yes	High	Yes	Yes



### 3.0 Direct Detection by Platform

Direct detection involves use of visual and remote sensing from vessels, aircraft, and satellites to locate the debris. JTMD detection efforts used multiple platforms, sensors, and observation methods, which are listed in this section. In addition, it highlights limitations and gaps for each platform in order to identify opportunities for future development and capacity building.

**Table 2 – Confirmed JTMD Sightings by Platform.**

<b>Platform</b>	<b>Potential JTMD Sightings</b>	<b>Confirmed JTMD Sightings</b>
<b>Vessels</b>	638	4
<b>Aircraft</b>	12	1
<b>Satellite</b>	0	0
<b>Shore-based Observations</b>	1270	41
<b>Totals</b>	1919	46

As shown in Table 2, more debris sightings have been from vessels (638) and shore-based observations (1270) to date, while fewer have been from aircraft (12) and satellite (0). Although fewer detection reports have come via aircraft and satellite, these platforms do have the ability to cover a larger area more rapidly than the other platforms, and have been useful in searches to relocate objects reported by mariners (as with the Misawa dock that washed ashore in Washington in December 2012). Similarly, while a greater number of sightings have occurred from vessels and shore-based observations, these were primarily opportunistic sightings from the general public, community groups, and companies or agencies already in the areas based on pre-existing purposes or missions who report on a voluntary basis, rather than targeted efforts or assets (e.g., vessels, aircraft, or staff) that are focused primarily on detecting marine debris. Opportunistic sightings are useful in detection efforts and essential in gaining information in remote areas. However, they also have limitations, such as a lack of consistency between reporting protocols and approaches, as well as predictability and control in coverage and frequency. As an example, a single report of a confirmed JTMD object by a vessel crew in one location is useful, but the overall utility is limited if it is not clear where that crew was before or after the sighting and if they saw anything, or were actively on the lookout for debris, in those locations. Reliable reporting on where debris was not seen can be almost as important as where debris was seen in order to inform and validate modeling parameters.

The remainder of this section is organized by platform type. Where appropriate, platforms are further subdivided by the environment where they are being used; at-sea or shoreline. Platform-specific limitations and potential actions to address those limitations are described in Sections 3.1-3.4 and summarized in Table 3.

- Detection Efforts – Summary of JTMD detection efforts until the time of this report;
- Limitations – List and discussion of limitations of detection;
- Possible Actions – List and discussion of possible actions to address the limitations.

**Table 3 – Detection Platform:** *Limitations and possible actions to address those limitations are listed by platform type. A general limitation is the lack of dedicated resources for use in targeted detection efforts, though significant progress was made during the JTMD response in building partnerships for opportunistic detection efforts across all platform types.*

Limitations	Possible Actions
<b><i>Vessels</i></b>	
<ul style="list-style-type: none"> <li>• Lack of dedicated resources (vessel time)</li> <li>• Dependence on voluntary/opportunistic participation</li> <li>• Physical structure of and line of sight from vessel</li> <li>• Dependence on weather conditions – sea-state, fog, rain, cloud cover, sun angle</li> <li>• Paperwork Reduction Act (PRA) approval process for reporting forms</li> </ul>	<ul style="list-style-type: none"> <li>• Identify vessel operators that are optimal partners in detection of debris at-sea, based on general structure of vessel fleet, areas of operation, and degree of voluntary participation in reporting</li> <li>• Conduct targeted outreach and education to partner organizations on the limitations identified in this report, and provide survey and observation guidelines that address those limitations (e.g., physical structure of vessel, line of sight restrictions, watch and observation schedules)</li> <li>• Design a split data stream approach that allows for more robust data collection and reporting (including active areas, methods used, common vocabularies and debris definitions) by interested partners, and separate short form and flexible reporting system for individual opportunistic sightings</li> <li>• Establish a reporting protocol for vessel operators that make routine voyages and include in the protocol a request to indicate whether or not survey or observation operations were conducted for each voyage, or for which part of each voyage</li> </ul>
<b><i>Aircraft: Open Ocean</i></b>	
<ul style="list-style-type: none"> <li>• Lack of dedicated resources (aircraft time)</li> <li>• Dependence on voluntary/opportunistic participation</li> <li>• Limited aircraft range, availability, and altitude</li> <li>• Dependence on weather conditions – sea-state, fog, rain, cloud cover, sun angle</li> <li>• PRA approval process for reporting forms</li> <li>• Aircraft operational constraints based on mission, aircraft type <ul style="list-style-type: none"> <li>○ Flight altitude</li> <li>○ Flight speed</li> <li>○ Flight range</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Request dedicated aircraft time</li> <li>• Conduct consistent reporting from long-range aircraft operating in areas of potential debris aggregation or movement</li> <li>• Identify aircraft operators that are optimal in detection of debris, based on aircraft range, availability, altitude and degree of voluntary participation with reporting</li> <li>• Conduct outreach to Department of Defense (DOD) and Department of Homeland Security (DHS) for inclusion of marine debris survey operations during training flights.</li> <li>• Determine and capture specific capabilities of sensors for detecting</li> </ul>

Limitations	Possible Actions
<ul style="list-style-type: none"> <li>○ Flight area</li> </ul>	<ul style="list-style-type: none"> <li>marine debris</li> </ul>
<b><i>Aircraft: Shoreline</i></b>	
<ul style="list-style-type: none"> <li>• Lack of dedicated resources (aircraft time)</li> <li>• Dependence on voluntary/opportunistic participation</li> <li>• Type of aircraft/availability</li> <li>• Shoreline terrain</li> <li>• PRA approval process for reporting forms</li> <li>• Aircraft operational constraints based on mission, aircraft type               <ul style="list-style-type: none"> <li>○ Flight altitude</li> <li>○ Flight speed</li> <li>○ Flight range</li> <li>○ Flight area</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Expand to Civil Air Patrol and other compatible flying organizations</li> <li>• Share Alaska shoreline survey protocols and compare lessons learned</li> <li>• Conduct outreach to Department of Defense (DOD) and Department of Homeland Security (DHS) for inclusion of marine debris survey operations during training flights over shoreline/near shore areas</li> </ul>
<b><i>Satellite</i></b>	
<ul style="list-style-type: none"> <li>• Sensor applicability for detection of small and mixed debris</li> <li>• Timeliness of data response (required time and staff possibly not available for analysis)</li> <li>• Ongoing access to satellite imagery</li> </ul>	<ul style="list-style-type: none"> <li>• Determine and capture specific capabilities of sensors for detecting marine debris</li> <li>• Develop control data showing signatures of known objects in different satellite sensor and resolution imagery collections</li> </ul>

Limitations	Possible Actions
<b><i>Shore-based Observations: Organized Shoreline Monitoring and Detection Efforts</i></b>	
<ul style="list-style-type: none"> <li>• Accessibility to some shorelines</li> <li>• Comparison with other existing data protocols</li> <li>• Difficulty (excessive rigor/sophistication) of NOAA Marine Debris Program (MDP) guidelines for some groups</li> <li>• Training of volunteers and partner organizations</li> <li>• PRA approval process for reporting form<sup>1</sup> for shoreline reporting</li> </ul>	<ul style="list-style-type: none"> <li>• Create a generally applicable, PRA-approved marine debris reporting form for opportunistic sighting and reporting (separate from regularly scheduled monitoring), usable in either in online or print format</li> </ul>

<sup>1</sup> Refer to Section 3.1 for more information.

Limitations	Possible Actions
<i>Shore-based Observations: Opportunistic Sightings</i>	
<ul style="list-style-type: none"><li>• Inconsistent coverage</li><li>• Lack of correlation between awareness and reports</li></ul>	<ul style="list-style-type: none"><li>• Continue education and outreach to the public on types of debris that should be reported, how to report found debris and on opportunities to participate in voluntary monitoring events</li><li>• Design a split data stream approach that allows for continuation of more robust data collection and reporting by interested partners, and a separate shorter form monitoring protocol and reporting system allowing groups or citizens to participate in shoreline reporting at a more accessible level</li><li>• Pursue options for use of emerging approaches for crowd-sourcing of citizen science information using social media, app-enabled reporting, or other distributed reporting mechanisms</li></ul>

### 3.1 Vessels

Direct detection from vessel platforms has primarily been based on visual observation from crew members. Ongoing opportunistic studies are investigating the use of unmanned aerial systems (UAS) equipped with sensors which can be launched from a vessel to help improve coverage and accuracy of direct detection at-sea, but those concepts are still in testing stages. More information on this work can be found in the aircraft platform section. However, while UAS tools are being tested for utility in multiple scientific missions, they have not yet been employed for systematic or wide-scale marine debris or JTMD detection. For debris detection applications, small UAS primarily have served to extend the visual range from a vessel for either targeted or opportunistic detection. Efforts to detect JTMD have been conducted primarily by visual bridge or deck observers on a voluntary basis from a variety of vessel types, which are described in Table 4, below.

#### *Detection Efforts*

NOAA worked with the U.S. Department of Transportation's Maritime Administration (MARAD) to alert ocean-going vessels of tsunami debris, and has asked partners across shipping, scientific, fishing, and recreational fleets, who regularly travel the Pacific Ocean, to report any significant sightings with as much information as possible (including location, date and time found, photos, and any relevant descriptions). This data call was also disseminated to commercial cargo fleets (through the World Ocean Council), commercial and recreational fishing vessels, scientific expeditions, and government vessels and fleets including NOAA's Office of Marine and Aviation Operations' Pacific fleet<sup>2</sup>, U.S. Coast Guard (USCG), U.S. Navy, and U.S. Fish and Wildlife Service. Contacts were also made through the National Weather Service Voluntary Observing Ship Program. Vessels were encouraged to use a pre-established marine debris visual survey reporting form<sup>3</sup>, and report sightings to a NOAA email account set up for JTMD reporting ([DisasterDebris@noaa.gov](mailto:DisasterDebris@noaa.gov)). Recreational mariners participated in reporting possible JTMD to NOAA—filling out the visual survey reporting form or emailing the DisasterDebris email account directly. In one specific project partner project called the TransPacific Marine Debris Visual Survey Project<sup>5</sup>, yacht racers reported possible JTMD and carried with them satellite-tracking buoys to deploy in case they spot large-sized debris or a concentration of marine debris at-sea.

These satellite-tracking buoys are pre-existing assets that NOAA has used for tracking derelict fishing nets and more general debris movement research programs. They were distributed to NOAA offices in each region for tracking any large-scale objects encountered on opportunistic or targeted cruises. Each buoy weighs roughly 11.5 kilograms and is approximately 45 centimeters in diameter by roughly 35 centimeters high. Partners deploy these buoys according to prescribed guidance by the NOAA Marine

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<sup>2</sup> Using NOAA form 57-11-14; not Paperwork Reduction Act (PRA) approved; available at [http://www.corporateservices.noaa.gov/~noaaforms/listings\\_pg6.html](http://www.corporateservices.noaa.gov/~noaaforms/listings_pg6.html)

<sup>3</sup> Using NOAA form 75-103; PRA-approved and available at [http://www.corporateservices.noaa.gov/~noaaforms/listings\\_pg7.html](http://www.corporateservices.noaa.gov/~noaaforms/listings_pg7.html)

<sup>5</sup> TransPacific Marine Debris Visual Survey Project (<http://mdsurvey.wordpress.com>)



Debris Program (MDP). The first of these buoys was attached to a large floating object by a recreational sailing vessel returning from Hawai'i to California in the fall of 2012. It transmitted position data for several days before the buoy signal ceased, potentially due to impact with the debris object in wave action. Buoys were also deployed to confirm and maintain awareness of the position of the Misawa dock that arrived on the Olympic Coast of Washington state in December 2012.

Table 4 – Vessel Types

Purpose	Operators	General Fleet Description	Area of Operation
<i>Commercial</i>			
<b>Cruise</b>	Industry	Sizes vary. Generally longer than 200 m	Varies, but primary routes are on set patterns between coastal ports of call. Vessels operate on common routes with pre-determined schedules
<b>Ferries</b>	Industry	Sizes vary. Generally longer than 50 m	Typically inland or protected waterways, with limited exceptions. Vessels operate on common routes with pre-determined schedules
<b>Fishing</b>	Industry	Sizes vary widely based on fishery	Varies, but generally localized by fishery
<b>Shipping (i.e., container ships, bulk cargo carriers, etc.)</b>	Industry	Multiple size categories. Larger ocean-going ships range in length up to over 360 m. Smaller ships that typically operate between smaller ports generally range from 100 m to 200 m	Varies by type and size of vessel and cargo. Vessels generally operate on common routes with pre-determined schedules
<b>Other (e.g., SCUBA charters)</b>	Industry	Typically smaller vessels (<20 m length)	Typically nearshore, with unpredictable schedule and routes
<i>Government/Academia by purpose</i>			
<b>Enforcement</b>	NOAA	Typically small vessels (<20 m length)	Typically nearshore, with unpredictable schedule and routes
	USCG	Lightship, Buoy Tender, Cutter, Icebreaker	Varies widely by vessel type, size and mission
<b>Military</b>	U.S. Navy	Carriers, Submariners, Sub Tenders, Mine Clearance, Surface Warfare (Battleships, Frigates, Patrol Combatants, Cutters)	Varies widely by vessel type, size and mission. Locations unavailable for security reasons
	USCG	Lightship, Buoy Tender, Cutter, Icebreaker	Varies widely by vessel type, size and mission.
<b>Research</b>	NOAA	Typically greater than 60 m in length	Varies widely by vessel type, size and mission
	Universities/ Other	Types and sizes vary.	Varies widely by vessel type, size and mission

<i>Non-government/Private</i>			
<b>Advocacy/ Research</b>	Non-profit and advocacy organizations	Types and sizes vary	Varies widely by vessel type, size and project/mission
<b>Recreational Boaters</b>	Private citizens	Size generally ranges from 2m up to longer than 50 m. Motorized and non-motorized	Varies. Generally unpredictable schedule and routes, apart from events

### *Limitations*

- Lack of dedicated resources (vessel time)
- Dependence on voluntary/opportunistic participation
- Physical structure of and line of sight from vessel
- Dependence on weather conditions – sea-state, fog, rain, cloud cover, sun angle
- Paperwork Reduction Act (PRA) approval process for reporting forms

The majority of at-sea or vessel-based JTMD reports were based on opportunistic sightings provided to NOAA by partner organizations and the general public. This is in part because dedicated resources (i.e., vessels or crews) for targeted wide-scale marine debris surveillance are not consistently available. While opportunistic reporting is highly valuable, it frequently leads to inconsistent and unpredictable spatial and temporal coverage within an area of interest. Additionally, while vessel traffic may pass through the area of interest - in this case the area of potential JTMD concentration and transit - routinely (considering shipping schedules, fishery locations, etc.), it was and is not usually known whether crews maintain a routine marine debris watch from the same location on the vessel and at the same time within the transit schedule. This consistency is unlikely because vessel crews typically are small in number and occupied with their work duties. Therefore, if no reports are received from an area or vessel, it is difficult to know whether this indicates a lack of debris within the area of the voyage or that no consistent observation/survey effort took place.

The physical structure of the vessel and the weather conditions at the time of observation are additional factors affecting visual detection from the vessel platform. In terms of structure, the success in seeing debris depends on the height of the vessel, location of the observer on deck, and the method they are using to survey and record any debris that is sighted. Because most sightings are opportunistic, standardizing survey and reporting methods is difficult, leading to varying levels of detail in reporting. Moreover, weather conditions, including sea-state, fog, heavy rain, cloud cover, or even sun glare can reduce or obscure visibility, making coverage from even an active observer unpredictable.

While some of these challenges could be addressed through a standardized reporting system, the Paperwork Reduction Act (PRA<sup>6</sup>) approval process makes implementing and distributing a written

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<sup>6</sup> 44 *United States Code* §3501 et seq. (1980)

standardized reporting form more challenging. The PRA approval process is triggered when a federal agency, such as NOAA, aims to request information from 10 or more persons in the public, and requires an Information Collection Request (ICR) be submitted to and approved by the Office of Management and Budget (OMB), which can take several months. This can make flexible and cooperative design of electronic and/or hard copy reporting forms for different platforms challenging.

### ***Possible Actions***

- Identify vessel operators that are optimal partners in detection of debris at-sea, based on the general structure and operational area of the vessel fleet and degree of voluntary participation with reporting.
- Conduct targeted outreach and education to partner organizations on the limitations identified in this report, and provide survey and observation guidelines that address those limitations (e.g., physical structure of vessel, line of sight).
- Design a split data stream approach that allows for more robust data collection and reporting (including active areas, methods used, common vocabularies and debris definitions) by interested partners, and separate short form and flexible reporting system for individual opportunistic sightings.
- Establish a robust protocol for vessel operators that make routine transits, and include in the protocol a request or requirement to indicate their route, and whether or not they conducted survey or observation operations for each transit, or for which part of the transit, in order to provide data on extent and coverage of debris sightings.

## **3.2 Aircraft**

For JTMD, direct detection from aircraft platforms was performed primarily via visual observation and deployment of sensors (i.e., visual and infrared). Similar to the vessel platform, detection efforts were primarily voluntary and conducted from different aircraft types operated by commercial, governmental, and non-governmental organizations, as well as by private citizens operating over both the open ocean and along shorelines. Different aircraft types were used within these areas. While the capabilities and flight profiles of different aircrafts and missions vary widely, a few examples of applicable aircraft types and missions are listed below for reference.

Along the shoreline, smaller aircraft, such as single or twin-engine propeller planes (e.g., Cessna 172, 182, etc.) or helicopters are frequently operated by contracted commercial companies, local government air patrol, or private citizens. These smaller aircraft may be equipped with visual or infrared sensors and typically operate at altitudes of 500 – 2,000 ft. when collecting data, with a variable range of 600-900 nautical miles (nm). Over the open ocean, larger aircraft such as C130s operated by the U.S. Air Force and the USCG, or research aircraft such as the P3 or Gulfstream IV operated by NOAA are potential options. The C130—a large, four-engine patrol aircraft flown by the USCG and USAF that has previously been used for debris detection efforts—has a range of approximately 2,000 nm and the ability to fly also at low altitudes (necessary for aerial surveys for marine debris). NOAA and U.S. Navy P3 aircraft, which are typically used for atmospheric research and patrol, respectively – have long range and are capable of flying at low altitudes. While both USCG C-130 and U.S. Navy P3 aircraft offer strong capabilities for debris spotting missions, flight time on either aircraft is rarely available based on existing missions and agency priorities. The NOAA Gulfstream IV, which was not used, has a range of approximately 3,800 nm

and operates at very high altitude, and is not designed for surface search, making it relatively limited in utility for debris detection missions.

A further variable is the familiarity of the onboard observers with open-ocean aerial surveys or searches for small objects such as marine debris. Some organizations, such as USCG, regularly practice this skill during other missions (search and rescue). Other organizations or individuals have skills that may offer parallels to debris detection operations, such as aerial wildlife surveys or other spotting and reporting of specific targets in the open ocean.

Small UAS were also tested on an opportunistic basis for debris detection capabilities as part of the overall response efforts. As mentioned previously, these systems have been primarily deployed in testing missions to evaluate their capabilities in adding value to existing operations or fulfilling specific missions or tasks to which they are suited (such as observation of sensitive species, which are less likely to be disturbed by the relatively quiet small UAS). NOAA partnered with other agencies on two tests of the Puma UAS system for marine debris detection at-sea, showing positive results in extending visual survey range from a vessel in the right conditions. Field reports for these two efforts are included in the appendix to this document.

### ***3.2.1 Open Ocean Aerial Detection***

This section describes aerial detection efforts by aircraft on the open ocean, limitations of these, and possible actions to address the limitations identified.

#### ***Detection Efforts***

Through the Federal Aviation Administration's Notices to Airmen, NOAA asked pilots to report sightings to the [DisasterDebris@noaa.gov](mailto:DisasterDebris@noaa.gov) account. The U.S. Air Force also volunteered to report any sightings during its North Pacific winter storms mission for the NOAA National Weather Service in February/March 2013. Additionally, USCG Districts 14 and 17 included voluntary reporting in their enforcement and general patrol missions in the Northwestern Hawaiian Islands and Alaska, respectively, and invited NOAA and other observers to accompany selected missions.

#### ***Limitations***

- Lack of dedicated resources (aircraft time)
- Dependence on voluntary/opportunistic participation
- Limited aircraft range, availability, and altitude
- Impact of weather to effectiveness, both in terms of capability to operate and in terms of visibility and probability of detection due to sea-state, rain, fog, sun angle, or other variables.
- Aircraft operational constraints based on mission, aircraft type
  - Flight altitude
  - Flight speed
  - Flight range
  - Flight area

Similar to observations on vessels, opportunistic aerial surveys can be inconsistent and unpredictable without debris-specific effort coverage of the target area. Moreover, targeted overflights are logistically

challenging and are not typically feasible, given available resources and missions already in place for capable aircraft. For JTMD, the diverse and widely spread nature of debris concentrations resulted in significant uncertainty for debris locations, and thus target areas, across the North Pacific Ocean. Additionally, coverage within many open-ocean target areas was outside the capability of all but the largest and longest-range aircraft, which are scarce in number and are in high demand because of their utility for other operations. The diversity and mixed composition of JTMD also requires detection operations from relatively low altitude (1000-2000 ft.) in order to be consistently successful in detecting debris objects that may be present, further limiting the effective range of aircraft. Finally, weather variables, including sea-state, rain, clouds, or sun glare, can also obscure or impact the observer's view, negatively impacting the success of detection efforts.

### ***Possible Actions***

- Request dedicated aircraft time.
- Conduct consistent reporting from long-range aircraft operating in areas of potential debris aggregation or movement.
- Draft and distribute protocol or guidance for aerial observation and reporting of at-sea debris for use by participating partners.
- Identify and coordinate with aircraft operators and onboard observers that are optimal for detection of debris based on aircraft range, availability, altitude, degree of voluntary participation with reporting, and observer experience/skillset.

It may be beneficial to identify a group of assets (equipment) operations (missions) and observers (people) that would be best suited for marine debris detection based on aircraft range, flight plan profiles, aircraft availability, and observer experience/skillset. Additionally, working to build partnerships with other agencies to facilitate collaborative missions that include targeted debris detection components would help build capacity for a future event.

### ***3.2.2 Shoreline and Near Shore Aerial Detection***

This section describes aerial detection efforts in shoreline and near shore areas, limitations of these, and possible actions to address the limitations.

#### ***Detection Efforts***

Individual states conducted targeted marine debris shoreline aerial surveys. The State of Washington and the State of Hawai'i have also leveraged partnerships with the Civil Air Patrol for opportunistic sightings. The shoreline surveying activities by the states are described in more detail as follows:

- **Alaska** – The Alaska Department of Environmental Conservation (ADEC) contracted with Airborne Technologies, Inc. (ATI) to conduct an aerial survey of shorelines in the Gulf of Alaska region, from Southeast Alaska at Dixon Entrance to Kodiak Island and Tugidak Island for tsunami debris. This survey yielded high-resolution photo imagery of beached debris and provided a snapshot of debris deposition at the time of the survey in July and August 2012. Nearly 2,500 miles were surveyed, resulting in over 8,000 high-resolution still images that were graded qualitatively for debris density on a 0 to 5 scale. These images indicated high debris depositions in historically high concentration areas, but it also highlighted the variable deposition



of debris based on local conditions. Overall, the data indicated qualitative trends in debris deposition, and it was later used in debris cleanup prioritization and planning efforts in Alaska. The survey used protocols previously established for small-plane-based aerial surveys of shorelines that had been used by both ATI and NOAA for previous shoreline debris surveys. The State of Alaska contracted with the same group to repeat and extend the survey in the 2014 field season, with the goal of updating and comparing debris deposition data between the two years for prioritization of ongoing and future cleanup operations.

- **Hawai'i** – USCG Auxiliary in Hawai'i received approval to assist in three dedicated overflights during November and December 2012 for JTMD on shore and within 10-25 miles from shores of Oahu, Kauai, and the Big Island of Hawai'i. Additionally, NOAA worked with the Department of Defense to conduct field tests to evaluate the effectiveness of small UAS in detecting simulated marine debris off Oahu as part of a larger UAS demonstration and evaluation effort in June, 2012. This test showed positive capability in detecting medium sized objects (~1 m +) with the base sensor package of the Puma UAS. A full report of this effort is attached in Appendix A.
- **Washington** – The Washington State Patrol Aviation Section conducted proof-of-concept targeted shoreline surveys. The Aviation Section uses Cessna fixed-wing aircraft to perform public safety missions, including Cessna 206 aircraft equipped with gyro-stabilized Forward Looking Infrared (FLIR) cameras. In addition, the Washington Wing – Civil Air Patrol provided information on opportunistic sightings of debris. The initial pilot project encountered difficulties in image collection and processing, limiting the amount of usable data that could be gathered.

In June 2013, NOAA Olympic Coast National Marine Sanctuary, U.S. Fish and Wildlife Service, the Olympic National Park and NOAA UAS Program cooperated to conduct UAS operations that included shoreline debris surveys. These surveys were planned primarily as test flights to evaluate the use of UAS for the annual seabird surveys conducted on the Olympic Coast but were expanded to collect imagery for shoreline areas en-route to and from the seabird survey areas, and an offshore debris detection evaluation. The UAS surveys were paired with on-site shoreline surveys to ground-truth and comparatively measure the effectiveness of the aerial sensors. An initial field report from the offshore debris detection effort is available in Appendix B.

### ***Limitations***

- Lack of dedicated resources
- Dependence on voluntary/opportunistic participation
- Type of aircraft/availability
- Shoreline terrain suitability for aerial survey
- Aircraft operational constraints based on mission, aircraft type
  - Flight altitude
  - Flight speed
  - Flight range
  - Flight area

Without dedicated resources, aerial survey coverage of the target area was inconsistent and unpredictable. The shoreline terrain also can affect visibility and detection probability. For example, visually detecting

debris along a rocky or rugged shoreline with many crevasses or heavy vegetation can be more difficult than detecting debris on a smoother terrain, such as a sandy beach. These factors play into decision making for the timing and overall operational approach for surveys. As an example, surveys in Alaska and the Pacific Northwest in early spring may detect more debris before foliage has grown to obscure the debris. Furthermore, a more complicated shoreline can increase difficulty of obtaining consistent flight and image data at the appropriate altitudes, and increase the safety risk of the operation. Because many flights are opportunistic, the standard flight profile is frequently a limitation because the pre-existing mission involves flying not at a low enough altitude or speed to effectively or reliably detect marine debris.

### ***Possible Actions***

- Expand to Civil Air Patrol or other compatible flying organizations in other states.
- Share Alaska shoreline protocols and compare lessons learned with efforts in other locations.
- Conduct outreach to Department of Defense (DOD) and other agencies for inclusion of marine debris survey operations during training flights over shoreline/near shore areas.
- Continue to evaluate opportunities for cooperative shoreline aerial surveys, using manned or unmanned platforms.

Each state impacted by JTMD approached detection of shoreline marine debris from aerial platforms differently. In preparation for future responses, states and partners can learn from one another by continuing to share experiences, protocols, and lessons learned. For example, the use of Civil Air Patrol for opportunistic sightings in Washington may be an option for other states. Additionally, shoreline protocols and lessons learned during the aerial surveys in Alaska may be shared with other states for informational purposes and for redistribution to the general public via appropriate state websites. This information may be useful for recreational pilots and others seeking to conduct shoreline aerial surveys. Finally, the DOD is a potential resource that may offer additional expertise and operational assets for shoreline marine debris detection. Outreach to the DOD could include a request for inclusion of marine debris survey operations during training flights over shoreline/near shore areas. Many of these connections were made through NOAA-facilitated interagency briefing calls, but further interactions between the multiple active state and federal agencies will ensure ongoing cross-pollination of ideas and methods.

## **3.3 Satellite**

Satellite-gathered sensor data has the potential to provide data over a much wider area than any other method. However, the highly varied composition and predominantly small size of debris means it is at the boundary of detection capabilities for most sensors. Table 1 lists possible sensor types. This section describes detection efforts via satellites, limitations of these, and possible actions to address the limitations.

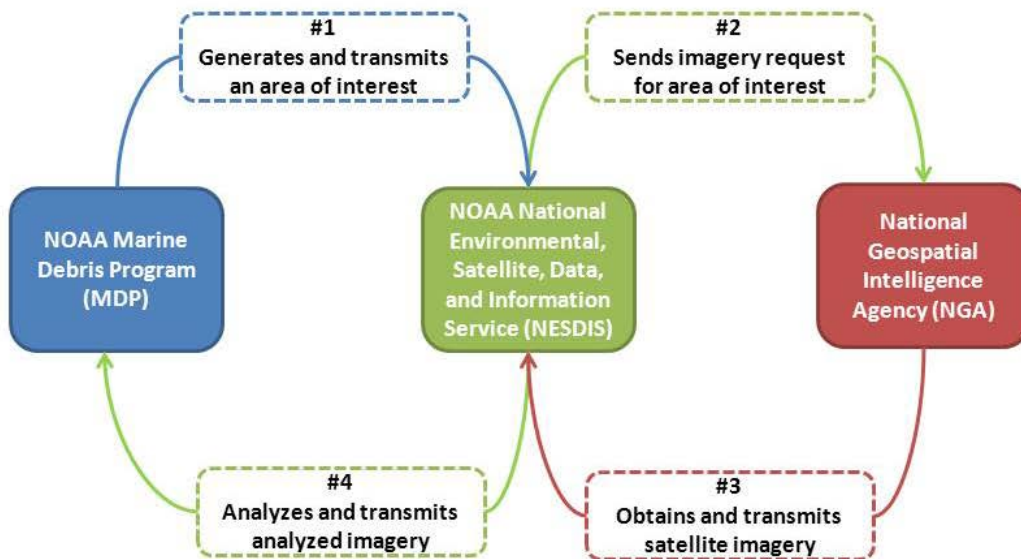
### ***Detection Efforts***

Immediately after the tsunami, images from multiple satellites became available from a variety of sources, including the U.S. Geological Survey, the European Space Agency's Rolling Archives, and a joint NASA/Japan Aerospace Exploration Agency website. Some of this imagery was provided through the International Charter on Space and Major Disasters, which provides short-term unrestricted access to satellite imagery in cases of identified disasters. NOAA NESDIS analyzed these data, and the results indicated large fields of debris were visible in 15-30 m resolution imagery. However, by April 2011, these fields of debris had dispersed such that items were no longer visible to these sensors, which were still focused primarily on the near-shore areas as part of the overall disaster response effort.

Based on the broad size diversity of debris that has been opportunistically sighted and confirmed as JTMD, sensors operating at high resolution (1-5 m) were expected to provide the best capability to detect the widest range of both general debris and JTMD, both by being able to detect smaller objects, and ideally by being able to differentiate different types of large objects from each other.

Beginning in early 2012, the NOAA MDP began working with the NOAA NESDIS Satellite Analysis Branch (SAB) to request higher resolution (1-5 m) satellite imagery from the National Geospatial-Intelligence Agency (NGA) for specific areas of interest as identified by the NOAA Marine Debris Program (MDP), based on modeling efforts. The sensors employed varied by the specific area of interest and data availability, but included Synthetic Aperture Radio (SAR) and visual and multispectral sensors, all at high resolution. Figure 2 shows the process by which the NOAA MDP requested and received satellite imagery from NGA. Once received, NESDIS SAB technicians processed the imagery. This group has continued to identify and evaluate new approaches and methods to analyze debris presence and absence throughout the response. This has included analysis of data from areas with known debris targets, as well as analysis of data from areas expected to have low debris density in order to provide context and comparison to data from areas of interest for JTMD.

Based on their results, NESDIS SAB shifted their approach over the course of the response to a persistence analysis method, whereby multiple images are taken of the same area a few seconds apart. Comparing the images allows for improved identification and disqualification of waves and other water features, which could otherwise be mistaken for debris.



**Figure 3 –JTMD Satellite Data Request Flow Chart.**

*Process by which NOAA MDP worked with NOAA NESDIS to request, process, and receive imagery and analysis outputs for identified areas of interest. Numbered action boxes are color coded to correspond with the acting organization (blue = MDP, green = NESDIS, red = NGA). NOAA NESDIS coordinated both the direct requests to NGA and the processing of the resulting imagery.*

NOAA also worked in the summer of 2012 with partners at NESDIS and NGA to codify a standardized Concept of Operations (CONOPS) for a JTMD Rapid Response Satellite Request, designed to increase the speed of rapid requests for acquisition and analysis of imagery to detect or confirm a large object of specific interest or threat. The trigger for this CONOPS was generally a sighting or other report of an object or objects that could pose a human hazard (hazard to navigation, hazardous materials, etc.) and are of size or in concentrations that could potentially be detected by satellite. The request process is the same as that shown in Figure 2; however, this is an expedited request with shorter turnaround time for acquiring and analyzing imagery. For rapid response requests, the goals are to obtain imagery within 24-72 hours of the request and analyze the imagery within a total elapsed time of 72-96 hours.

To date, no confirmed debris sightings have occurred via satellite. NESDIS SAB, which performed the analysis, indicated that cloud cover and sea-state have obscured the majority of the images obtained. In cases where there was good visibility, detection or identification of small (<2-3 square meters) objects was difficult, though the presence of large objects or aggregated fields of debris could be ruled out.

In cases where an anomaly was detected, identifying it as marine debris remained a challenge, based on the detection versus identification difficulties previously identified in this report. Those challenges are complicated by the fact that, as previously noted, JTMD types and compositions were and are very diverse, so the satellite sensors and analysis approach cannot be optimized to target any one specific size, shape, or composition of debris. Rather, the sensor or mix of sensors must be able to identify diverse debris items within the target areas.

### ***Limitations***

- Sensor applicability for detection of small and mixed debris
- Staff time and effort required for imagery analysis
- Timeliness of data response (required time and staff possibly not available for analysis)
- Ongoing access to satellite imagery due to other mission priorities

As indicated in Section 2.1.4, a wide range of possible sensors have been considered, though these sensors were developed for applications other than marine debris detection. Initial results show that visual and multi-spectral data were the most useful in debris detection efforts, while Synthetic Aperture Radar (SAR) sensors were less useful based on the lack of consistent large debris targets, and the inherent difficulty with identification with radar data. Further field testing could be beneficial in narrowing the field and possibly identifying the optimally appropriate sensor(s).

Processing satellite imagery is labor intensive because of the large number of satellite images produced for one target area and the many steps required to evaluate the imagery for debris presence or absence. The images—typically at 1 m resolution—require both automatic and manual analyses, cross-checks to identify any potential anomalies, and then further analysis to determine if a detected anomaly may be marine debris. These analyses occur based both on the signature of the object in the imagery and the persistence of the object (natural phenomena such as breaking waves do not appear on successive images). Because little control data are available to define the “signature” or “profile” for marine debris (what the debris looks like) in a satellite image, the confirmation process is often inconclusive. Moreover, competing priorities can decrease staff availability for these analyses.

Additionally, consistent access to satellite data and analysis resources was and is a long term limitation both for JTMD efforts and future efforts. The NGA was a primary resource for obtaining satellite data and has been highly supportive of JTMD detection efforts. The mission of NGA is to provide timely, relevant, and accurate geospatial intelligence information in support of U.S. national defense and natural disasters. Given this, on a long-term basis (beyond the time span for detection efforts of JTMD), the capability to request satellite imagery from the NGA may be diminished, reducing the capability to track debris consistently from the time of release in an acute event through to the time items are so widely dispersed that they can’t be detected even by high resolution sensors (in the JTMD response, debris data from immediately after the event was from mid-resolution imagery focused nearshore).

Finally, NESDIS SAB has been highly supportive of the debris detection mission, providing analysis and consultation throughout the response as part of their base support to NOAA and other clients. This support has been instrumental in advancing the understanding of the strengths and limitations of debris detection using satellite sensors under real-world conditions. The capabilities that have been and will be developed will help in selecting and applying the best mix of satellite imagery to collect and analyze in future acute debris release events.

### ***Possible Actions***

- Identify, document, and communicate the specific capabilities of sensors for detecting different types of marine debris under different sets conditions.
- Develop control data showing signatures of different types of debris object by size, composition and stage of degradation.

To improve analysis of satellite imagery, it would be helpful to develop control data or a “search image” of what marine debris looks like in data from each of the satellite sensors likely to be used in detection activities. NOAA most recently attempted this in a June 2012 field experiment in Hawai‘i. NOAA and NGA tested satellite detection of simulated in-situ debris off of Haleiwa, on the north shore of Oahu. Simulated debris objects, deployed from a chartered vessel offshore of Oahu, were designed to present diverse target profiles during six satellite passes, using multiple sensors. The objective was to evaluate effectiveness of different sensors and identify potential debris “signatures.” Unfortunately, results of this test were inconclusive via the most applicable visual and multi-spectral sensor types due to local cloud cover. As mentioned previously, a more complete report of this effort is available in Appendix A. Additional tests of this type may help in developing control data for analysts working to process satellite images of possible debris in the future, and are of continuing interest to NESDIS, as well as the overall marine debris community.

### **3.4 Shore-based Observations**

As mentioned previously, NOAA found that most of the marine debris generated by the Japan tsunami is difficult to distinguish definitively from the normal marine debris that washes ashore every day in Hawai‘i, Alaska, and along the West Coast of North America. Although some objects may have unique identifiable markings such as a name or license/registration number, the number of these objects compared with other types is low. As a result, primary indications that JTMD items were making landfall within a region could at times best be detected by tracking changes in the quantity or composition of debris compared to what was normally observed within that region. To identify these increases, NOAA worked with partners to collect (and is continuing to collect) shoreline monitoring data and opportunistic debris sighting reports.

#### ***3.4.1 Shoreline Monitoring and Detection***

This section describes detection efforts via shoreline monitoring and detection, limitations of these, and possible actions to address the limitations.

##### ***Shoreline Monitoring Efforts***

NOAA worked with federal, state, and local partners to acquire baseline information on the marine debris currently deposited on U.S. coastlines, along with, and in advance of, the expected influx of tsunami debris. These efforts are detailed in a separate document (Lippiatt et al., 2013) but are briefly summarized here. Using standardized shoreline monitoring protocols developed by the NOAA MDP, baseline marine debris surveys were conducted regularly on shorelines in Alaska, California, Oregon, the Hawaiian Islands, and Washington over a 2-year period. For example, NOAA worked with Sustainable Coastlines Hawai‘i and other non-governmental organizations to monitor shorelines across the main Hawaiian Islands. On the West Coast, Olympic Coast and Gulf of the Farallones National Marine Sanctuaries engaged their volunteer networks to establish monitoring sites. In southeast Alaska, a NOAA team conducted vessel-based surveys at multiple sites during summer 2012 and 2013, evaluating new NOAA MDP protocols and extending a time series of marine debris monitoring data for the state that dates to the 1980s.

These shoreline monitoring results helped identify the types of items arriving onshore and when and where JTMD may be making landfall, based on changes in both composition and quantity of debris over time. NOAA has developed a database to capture and catalogue the monitoring results for ongoing analysis and comparisons with future debris accumulation data.

High Frequency (HF) radar was also considered for shoreline-based detection but ultimately ruled out for future action. HF radar is a system used to measure surface current direction and speed. After evaluation and consultation with subject matter experts, NOAA concluded that HF radar is not likely to directly detect debris within its coverage area. This is primarily because objects could only be detected by HF radar if they are large (over 10-20 m). Also, the objects must move against the current, and debris typically moves with the current. This is because HF radar is typically used to detect and measure currents, so objects can only be distinguished based on differences in speed and direction from the speeds of the currents the radar sets are designed to detect.

### ***Limitations***

- Accessibility to rugged and/or remote shorelines
- Lack of consistency/predictability of shoreline coverage by visual or sensor-driven detection efforts
- Challenges in comparison/standardization with other existing data protocols
- Training of volunteers and partner organizations
- Level of complexity and time required for shoreline monitoring protocol exceeding capacity/availability for some partners
- PRA approval for reporting form<sup>7</sup> for shoreline reporting

In remote locations, establishing a monitoring site is more difficult. This limited accessibility can lead to inconsistent coverage of the coastline both by number of sites and by frequency of data collection. In addition, while the NOAA shoreline monitoring protocol was well received and adopted by many groups, the level of complexity and training it required was an obstacle for some groups whose field and/or training times were limited. This also contributed to limited or uneven coverage.

### ***Possible Actions***

- Continue coordination with groups, agencies, and citizens that collect observations or conduct monitoring for other topics issues.
- Design a split data stream approach that allows for continuation of more robust shoreline monitoring by interested partners, and creates a separate shorter form monitoring protocol and reporting system allowing groups or citizens to participate in shoreline reporting at a more accessible level.
- Pursue options for use of emerging approaches for crowd-sourcing of citizen science information using social media, app-enabled reporting, or other distributed reporting mechanisms.

### ***3.4.2 Opportunistic Sightings (Shoreline & Near Shore)***

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<sup>7</sup> Refer to Section 3.1 for more information.



This section describes detection efforts via opportunistic shoreline sightings, limitations of these, and possible actions to address the limitations.

### ***Detection Efforts***

Public and media interest in JTMD has been high. This has in turn led to a high number of opportunistic reports of potential JTMD from beach-goers in states across the Pacific region. Resources such as the NOAA MDP website and state and local government websites have provided guidelines and information on how and where to report marine debris. The specific information varies, but generally includes guidance on safe handling and appropriate reporting based on the object type and any special characteristics (personal markings, evidence of invasive species, etc.). Sightings are primarily tracked through NOAA's JTMD-specific reporting email system at [DisasterDebris@noaa.gov](mailto:DisasterDebris@noaa.gov). However, state and local governments have in some cases also established their own web reporting forms, phone hotlines, or email addresses in order to build awareness and integrate sightings response into existing structures. In those cases, sightings were shared with the NOAA reporting system, though at times this created the need to expend effort in finding and removing duplicate reports.

### ***Limitations***

- Inconsistent and unpredictable reporting effort/coverage by the public based on seasonality, accessibility and visitation
- Increased awareness being driver of increased reports, rather than increased debris densities

As could be expected, the increased interest in JTMD drove an increase in reports of possible JTMD as awareness and observing effort increased. Likewise, there were more reports from public beaches and shoreline areas with frequent visitors than from shoreline areas with limited access. This led to inconsistent coverage and relatively more reports from more accessible areas and areas with more traffic, which may not in fact have had the highest debris loads. However, many of these reports were of debris items that are likely to be general debris and not JTMD, though they cannot be confirmed either positively or negatively based on their general nature.

### ***Possible Actions***

- Continue education and outreach to the public on types of debris that should be reported, how to report, and opportunities to participate in organized volunteer monitoring events.
- Work with partners to draft and publish a less sophisticated, PRA-approved marine debris reporting form for opportunistic sighting and reporting (separate from regularly scheduled monitoring).

Since public interest in JTMD was high starting with the event and initial sightings, it provided an important opportunity to inform more individuals on the general marine debris issue and increase participation in shoreline monitoring events, local cleanups, and encourage behavior modification that reduces the chronic long-term introduction of marine debris. From March 2011 through the time of this writing, NOAA held more than 100 public meetings throughout Alaska, California, Oregon, Hawai'i and Washington, and conducted hundreds of media interviews on JTMD. NOAA and partner organizations have prepared webpages dedicated to the topic with fact sheets, brochures and other educational resources available for download. This type of activity should be continued into the future where possible, with a focus on public engagement and education.

## 4.0 Conclusion

Marine debris is an ongoing problem with day-to-day impacts. The Japan tsunami and other natural disasters both contribute to and raise awareness of the problem. The Tōhoku earthquake and the tsunami it caused were tragic events that created catastrophic damage onshore in addition to the debris they released into the ocean. One positive aspect that can be taken was the unprecedented opportunity for the marine debris community to learn invaluable lessons on the behavior and movement of marine debris, and a better understanding of the marine debris community's capabilities, limitations, and needs in modeling and detecting that debris as it migrated across the Pacific.

For both general marine debris and the JTMD, reliable detection and reporting is important to helping us better understand the quantity, composition and movement of floating debris and better assess and prepare for the potential impacts it might cause. In the case of the detection efforts for JTMD, while there was significant involvement and engagement from the public and agencies at the federal, state and local level, many of the lessons-learned illustrated the significant challenges and limitations that come into play when searching for diverse objects in a very large potential debris zone.

Opportunistic ship and shore-based sightings provided the majority of data inputs to the marine debris community, either through the [DisasterDebris@noaa.gov](mailto:DisasterDebris@noaa.gov) reporting system, or through various state and academic reporting systems. These were an invaluable source of qualitative information on overall debris trends at the aggregate level, and in the case of confirmed objects, they also provided definitive evidence of the spread of JTMD. For future events, building a more robust reporting system that is intuitive for the user but still provides consistent data that can be easily shared within the marine debris community – including responders, researchers, and public outreach personnel – is a clear opportunity to increase capacity and improve detection.

A key feature of a future reporting system should also be the ability for interested mariners or aviators to report not only debris sightings, but also report routes traveled and areas where no debris was sighted. This information, while not as intuitively useful, can be invaluable as an input to modeling efforts, and also can help provide a clearer picture of how debris is moving over time.

Aerial detection of marine debris has been shown to be effective both on shore and at-sea, but it is also very logistically challenging given the high cost and demand for aircraft time. This is exacerbated when target areas are more remote and require both more time and more capable aircrafts. In JTMD detection efforts, aerial detection at-sea was primarily dependent on voluntary/opportunistic reporting from government aircraft performing their primary missions. To prepare for future events, it will be important to maintain awareness and contacts with agencies and organizations that regularly conduct aircraft operations and to develop methods for them to easily report any debris sightings. Additionally, identifying overlaps in mission designs that allow for debris surveys to be incorporated more easily will help target outreach and requests in the event of a future event that triggers an acute release of marine debris.

Shoreline aerial survey for marine debris was successful in areas where a consistent protocol and experienced crews were available (Alaska), but less successful in areas where less structured methods

were used. In all areas, shoreline aerial survey is highly dependent on weather, and requires significant effort in post-processing to create a product that is informative for assessment and/or operational planning.

Satellite detection has been an area of significant effort and interest within the marine debris community, as well as the public, especially for distant, open-water areas. While direct detection of small objects has proven to be difficult with commercial satellite data, the data and results have been very valuable, in concert with opportunistic reports, in confirming the lack of any large debris concentrations or “islands”, which was a public concern throughout the JTMD response. Furthermore, the efforts have provided an invaluable opportunity to evaluate satellite collection and analysis techniques using a real-life debris scenario. Based on results to date, in a future event maintaining active surveillance of debris as it disperses from the source would offer the best chance at establishing clear thresholds for successful detection in terms of debris density and size. It is also clear that only high resolution (<5m) sensors should be used for debris after it has scattered. However, as resolution increases, coverage area decreases in a natural trade-off that gives a “soda-straw” view of an area of interest, reducing the coverage area that can be surveyed and increasing the post-processing effort on a per-area basis. It is important to take this trade-off and a realistic expectation for the capabilities and limitations of satellite sensors in general into account when scoping and planning satellite detection efforts. Development and testing of analysis techniques is ongoing, and will continue to be an important opportunity for building of capacity and understanding for future responses to acute debris release events.

A common challenge across all remote sensing approaches (primarily satellite, but aerial and UAS efforts as well) was the difference between detection and identification of a target or anomaly. When a target is at the edge of a sensor’s capabilities for resolution, it can be consistently possible to detect the object but much more challenging to identify or distinguish it with any certainty. As the resolution and sophistication of commercially available remote sensing data continues to increase, this challenge may well become less of a limiting factor in debris surveys. However, the increase in availability of high-resolution sensors in the long term will also likely increase the need for automated anomaly detection analysis of imagery to prevent a shift of the limitation from sensor capability to analysis time and effort.

Efforts to address these limitations through planning and partnerships continue and will require ongoing collaboration and communication across the marine debris community, including federal, state, local and tribal government as well as partners in industry, academic and non-governmental circles.

## 5.0 References

Lippiatt, S., Opfer, S., and Arthur, C. 2013. Marine Debris Monitoring and Assessment. NOAA Technical Memorandum NOS-OR&R-46.

National Atmospheric and Oceanic Administration (NOAA). 2012. "NOAA's Japan Tsunami Marine Debris Response Update." Draft, July 25.

## 5.0 Appendices

### 5.1 Appendix A – June 2012 Debris Detection Testing Report

NOAA DEBRIS DETECTION TESTING – JUNE 19-20, 2012

INTERIM REPORT – JULY 3, 2012

#### **SUMMARY:**

On June 19 and 20, 2012, NOAA and the National Geospatial-Intelligence Agency (NGA) conducted testing of satellite detection of simulated in-situ debris as part of a previously scheduled Unmanned Aerial Systems (UAS) test off of Haleiwa, HI. Simulated debris objects were successfully deployed from a chartered vessel offshore of HI, designed to present diverse targets for a total of six satellite passes using multiple sensors, as well as the visual and infrared sensors on board the Puma UAS. This test targets evaluation of detection capabilities across multiple sensor types against controlled/simulated debris to evaluate effectiveness and identify potential “signatures” to inform ongoing analysis. UAS sensors were able to clearly image the debris objects, as expected. Some satellite passes were impacted by cloud-cover while others were unaffected. NOAA NESDIS and NGA are analyzing satellite data, with additional outputs expected in coming weeks.

#### **BACKGROUND:**

One of the chief ongoing questions in the response to marine debris generated by the Japan tsunami is identifying the location, composition and quantity of the debris left afloat. Japanese government estimates indicate that 1.5 million tons of this debris was drawn back into the Pacific Ocean by the retreating wave. This debris spread out to the point that low-resolution satellites could no longer detect it past early April 2011. Since then, NOAA has been working with partners in USCG, NOAA NESDIS, and the NGA (National Geospatial Intelligence Agency) to model and detect the movement and distribution of this debris, now understood to be spread widely into a very large target area (estimated to be roughly 3x the size of the continental United States). To date, NOAA has requested over 400,000 square kilometers of high-resolution imagery, targeted based on modeling and opportunistic observation inputs, with no debris sightings confirmed and limited anomalies under ongoing investigation. While some of this area has been obscured by cloud cover or compromised by sea-state, in cases where imagery has been unobstructed, the question remains whether sensors are not detecting debris because it is not present in the target areas, or if the sensors themselves are not capable of detecting smaller debris objects that are believed to comprise a significant component of the total quantity of debris. Better understanding the effectiveness, or ineffectiveness, of these sensors will aid in future detection efforts



in selecting the correct mix of sensors and target locations to inform modeling, planning and response efforts.

**EFFORT:**

In order to directly test the ability of satellite-based sensors to detect debris, NOAA deployed simulated debris objects from a vessel previously scheduled to take part in trial operations of the Puma UAS (Unmanned Aerial System) in restricted airspace off the north shore of Oahu (green-shaded area in image). This area was chosen because UAS operations are limited by airspace permitting to operate within specific airspace and under specific clearance.

In this test, 12 simulated debris objects were deployed from a charter vessel, rigged at regular intervals on a long line to prevent loss and track location to inform satellite analysis. These objects were assembled to mimic common debris items by composition and size, ranging from fishing nets to metal small debris. The deploying vessels themselves were also important targets for detection, as they represent larger targets of varying compositions.

A total of six satellite passes were tasked to collect imagery in a small (~5 km x ~5 km) target area where debris was deployed, at times ranging from 6:20 AM to 6:38 PM. Satellite sensors ranged from Synthetic Aperture Radar (SAR) to Visual and Multispectral data.

During mid-day satellite passes, occurring between 11:20 and 11:30 AM, the Puma also overflew the debris, as well as other simulated targets. This is a precursor to later testing of both the Puma and Resolution UAS systems prior to deployment in 2013 for debris detection.

More details on the operation, including diagrams of the area, images of sample debris and support assets can be found in the supporting graphical operational report.

**RESULTS:**

As expected, the Puma system was able to detect and identify the debris objects with high accuracy and repeatability while operating at altitudes of 200-500 ft. While debris detection was not the primary focus of the UAS trial operation, these outputs will be instructive in the structuring of later tests in September/October, pending completion of new optical sensor payloads for both the Puma and Resolution UAS.

Visual / multispectral passes were at least partially obscured by cloud cover, illustrating the unpredictable applicability of visual detection. However, SAR passes in the early morning and evening of 06/20 will be unaffected by cloud cover. Analysis of all data is ongoing at the time of this report (07/03/12), with additional outputs expected in coming weeks.

For more information on this project, please contact

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## 5.2 Appendix B – June 2013 Olympic Coast UAS Debris Detection Testing Field Report

Olympic Coast UAS Survey Operation

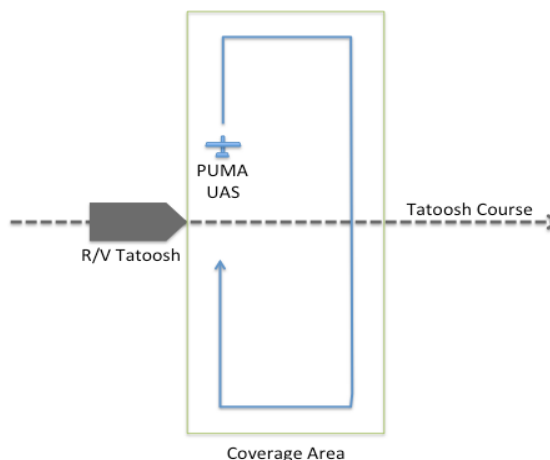
Debris Mission Report

*Peter Murphy, NOAA Marine Debris Program*

**Summary** – In June 2013, the NOAA UAS Program cooperated with U.S. Fish and Wildlife Service, NOAA Olympic Coast National Marine Sanctuary Working as part of a larger pilot project to evaluate the use of UAS assets in scientific missions on the Olympic Coast. The project had three components; shoreline seabird survey, shoreline debris detection, and at-sea debris detection. Shoreline debris detection was conducted on an opportunistic basis integrated into the overall seabird survey plan. At-sea detection operations were conducted as the schedule for the primary seabird survey operations allowed. Working within these considerations, a total of one day of at-sea detection operations was conducted based from the NOAA R/V Tatoosh, roughly 20 miles offshore WSW of La Push, WA. During this day, NOAA AOC crew flew three Puma sorties, taking advantage of favorable weather to combine two survey plans into a single day. Two debris objects were sighted visually during these sorties, and post-processing is ongoing to identify any other potential debris objects.

**Background** – The specific detection areas were selected based on satellite sea-surface temperature data showing surface convergence zones. A total of four survey days were planned based on the convergence data. The concept of operations for the Puma UAS system were planned to optimize coverage area at altitudes estimated to successfully detect debris objects of roughly 0.25 square meters.

**Methods** – Offshore debris survey 06/22 – Offshore debris surveys were based from the R/V Tatoosh. Waypoints for vessel travel were designated with the goal of crossing sea surface temperature fronts, as these were expected to create convergence and potentially higher debris concentrations. The Puma system was launched from the deck of the Tatoosh, and followed a pre-programmed search area set as a fixed rectangular area measuring 1 mile to the port and starboard of the vessel, and 0.5 mile fore and aft relative to the position of the control station on the vessel. The UAS then flew a course calculated to maintain position in advance of the vessel, and cover as much area within the rectangle as possible, as illustrated in the image below. Because the vessel was in motion, the actual course of the UAS appeared diagonal in order to maintain pace with the moving ground station.



A total of three sorties were flown during the survey day. Initial survey was done at 500 ft altitude, while later sorties were flown at 400 ft to allow for increased resolution on potential debris targets.

During each sortie, the NOAA AOC pilots managed the aircraft and reported any notable objects sighted in the aircrafts field of view. An additional observer watched the mirrored aircraft view display for objects, noting concentrations of marine vegetation that could also indicate areas of convergence. The ship's crew (captain and mate) also observed the horizon for potential debris objects. Any sightings were logged in order to aid post-processing, which was to be performed by Airborne Technologies, Inc.

**Results** – Three total sorties were conducted, with each flight lasting 1-2 hrs. Due to favorable weather conditions, the crew was able to combine two survey day plans into one operational day. A total of two (2) confirmed debris objects were sighted during the surveys: a small orange buoy, and a small white buoy. However, there were numerous anomalies that will be further evaluated in post-processing by Airborne Technologies, Inc.

**Primary Outputs** – *Overall, the Puma system performed very effectively in the open ocean debris detection testing mission. The survey planning software allowed for consistent coverage of an area relative to the vessel position, and resolution was sufficient for identification of objects at the targeted size. During the operation, additional points for future consideration and note were identified, these are captured below.*

1. **Weather Tolerance** – When operating in open water, the sea-state frequently became a controlling factor for safe retrieval of the aircraft from the water before winds would have restricted actual flight operations. While this is intuitively correct based on wind effect on waves in open water, it places an emphasis on sea-state in operational planning.
2. **Sensor Resolution** – The base five-megapixel payload on the Puma provided sufficiently detailed imagery for detection of objects (noting their presence), though identification (determining what the object actually is) was challenging. This capability will be improved by the development of higher-resolution sensors mated to the Puma system, which are understood to be underway by Aerovironment and other firms.
3. **Field of view** – The base sensor payload on the Puma has a relatively limited field of view in comparison to a human observer. While this can be compensated for during survey operations through route planning, it can be a challenge if an object is sighted and the operator wants to return to revisit that object. This is more easily done on-shore, but at-sea where there are very few points of reference and the base-station is in motion it can be difficult to reacquire a given object or area once the vehicle -and thus the camera - has passed over it. This emphasizes the importance of advance survey planning.

**Conclusion** – The Puma system has significant advantages in extending visual survey range from a given platform as well as in accessing focused/small areas of difficult or restricted terrain eliminating the risk to crew and minimizing or even negating impact or disturbance to species or habitat. Survey ranges are limited based on a combination of aircraft range and airspace clearances, making small UAS primarily valuable in localized operations at present. However, the combination of portability and low impact make small UAS such as the Puma a potentially highly valuable tool for debris detection and survey operations as a piggyback to existing vessel operations, or as a primary mission in focused shoreline areas where access is restricted by topography and safety or the presence of sensitive species.



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