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At-sea detection of marine debris: Overview of technologies, processes, issues, and options

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ABSTRACT

At-sea detection of marine debris presents a difficult problem, as the debris items are often relatively small and partially submerged. However, they may accumulate in water parcel boundaries or eddy lines. The application of models, satellite radar and multispectral data, and airborne remote sensing (particularly radar) to focus the search on eddies and convergence zones in the open ocean appear to be a productive avenue of investigation. A multistage modeling and remote sensing approach is proposed for the identification of areas of the open ocean where debris items are more likely to congregate. A path forward may best be achieved through the refinement of the Ghost Net procedures with the addition of a final search stage using airborne radar from an UAS simulator aircraft to detect zones of potential accumulation for direct search. Sampling strategies, direct versus indirect measurements, remote sensing resolution, sensor/platform considerations, and future state are addressed.

1. Introduction

Marine debris, consisting of derelict fishing nets, buoys, and ropes, wash up on shores, become entangled in reefs, and endanger threatened species and habitats. The National Oceanographic and Atmospheric Administration (NOAA) is seeking a means to remove these debris at-sea before they become a threat to critical habitats, such as the Papahanaumokuakea Marine National Monument in the Northwestern Hawaiian Islands (Morishige and McElwee, in press). As with any environmental monitoring problem, it is important to understand the problems posed by at-sea detection of derelict fishing gear (DFG) as well as the characteristics and behavior of the debris themselves. This paper, and the companion papers in this issue, bring together the modeling, remote sensing, and environmental knowledge gained so far in developing a strategy to effectively remove DFG before they reach near coastal waters. This paper discusses the rationale behind a multistage modeling and monitoring option.

Derelict fishing gear items are small objects, relative to the spatial resolution of most survey-level remote sensing instruments, and they are primarily submerged (McElwee and Morishige, 2010). Their extent on the surface is typically a square meter or less, with a tangled knot of plastic netting, ropes, and other materials descending downward in the water column for several meters. Though marine debris items are highly significant to marine life and to marine habitats, they are relatively rare events, infrequent, relative to the expanse of the ocean. This requires a search strategy that operates at multiple scales to be successful within the confines of available resources. Moreover, it is desired to detect and remove nearly all instances that threaten critical habitats and species. No single technology or solution will enable detection and cleanup. An integrated systems approach will be essential. In developing an integrated approach, it is important to understand differences between different types of sampling strategies, the difference between direct and indirect measurements, and how remote sensing resolution affects detection. We will also need to understand how telecommunications, data processing, sensors, and platforms are matched to provide actionable information.

2. Search and sampling strategies

Since derelict fishing gear (DFG) items are relatively small and rare, it is impractical to canvass the entire ocean for them. A sampling strategy must be employed to efficiently search for them. Spatial sampling can be systematic or stratified. For systems in which there is very little *a priori* knowledge of the spatial distribution of targets, a systematic sampling scheme is most appropriate.

The US Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) is an example of this strategy. EMAP's goal was to produce regional and national assessments of the health of ecological resources for the United States. A global grid was developed, based on tessellated hexagons (White et al., 1992). The grid was developed to preserve the objectives of "equal area, equal and compactly shaped sub-divisions with minimal scale distortion, and a hierarchical structure for enhancement

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and reduction" (White et al., 1992, p. 7). Field sampling was conducted within each hexagon area to characterize environmental health. While this was a highly efficient and successful strategy for resources that occur at kilometer scales, and sub-divisions can be created for regional, state, and local, as well as national scales (EPA, 1993), the number of sample locations required for DFG detection would be so large it would approach canvassing the ocean.

Meter and sub-meter scale rare objects require stratified sampling for detection or characterization. Stratified sampling uses *a priori* knowledge and spatial analysis to develop a regionalization scheme. Samples are taken in each stratum in proportion to its area. Better *a priori* knowledge yields greater sampling efficiency and higher probability of detection. In the case of DFG, we are interested in going beyond estimates of quantity to cleanup of all articles. Therefore, high probability strata should be canvassed fully. Lower probability strata can be sampled as part of a quality assurance program.

There is sound evidence that debris can congregate in eddies and convergence zones in the open ocean. Therefore, the first level of stratification is to determine the likely location of these features at the scale of ocean basins. This is discussed more fully in a companion article (Howell et al., in press). Further stratification can be developed through the use of satellite- and aircraft-based remote sensing. This basic process was investigated by the Ghost Net Project and found to be a reasonable approach (Pichel et al., 2003).

3. Direct and indirect measurements

Once the strata are determined, measurements must be made to locate the debris. Measurements to locate derelict fishing gear at-sea can be direct or indirect. Direct measurements use the characteristics of the debris materials to establish presence or absence through contact or through remote sensing. A good analog of this is the visual sighting of an orange raft by the US Coast Guard during a rescue operation. The Coast Guard has developed detailed search patterns for air and sea craft which optimize the visual detection of the raft (personal communication with Arthur Allen). Visual detection is also optimized by the characteristics of the raft (brightly colored) and by the use of dyes in the water, signal mirrors, and flares to enlarge or enhance the object (figure) versus the ocean (ground).

Indirect measurements use the characteristics of the environment to map the regions in the ocean where DFG are more likely to be found. They are highly dependent on our knowledge of the behavior of the debris in the marine environment as well as our ability to detect the collection of conditions that increase likelihood of discovery. This often begins with a model which reflects the behavior of the debris and their interactions with the marine environment. This is followed by observations over large areas at coarse spatial resolution to detect and map regional conditions. Higher-resolution measurements are then made over reduced areas to detect and map the specific areas of high likelihood for the debris (desired strata). If densities are known, amounts of material can be calculated, and vessels can be directed to the areas for visual search. Remote sensing resolution becomes a key factor in developing an effective approach.

4. Remote sensing resolution

Remote sensing resolution becomes central to the use of direct detection and is an important variable in conducting broad area surveys for indirect detection. Remote sensing resolution may be in terms of spatial, spectral, or temporal dimensions. Each of these limits the others and drives cost of the survey. All remote sensing systems are a compromise between these resolution variables. Moreover, detection is highly sensitive to thresholds. The trade between cost and resolution can often determine success or failure.

Spatial resolution is a common driver for survey costs. Increasingly small instrument instantaneous field of view (pixel size) usually yields a narrower total field of view (swath width), produces a larger data set size for a given area, and, especially for satellite systems, reduces temporal resolution (increases time for repeat measurements and for full area coverage).

Spectral resolution affects processing and data storage but also affects detection ability. Increases in spectral resolution enable sub-pixel object recognition, but also increase data set size, decrease signal-to-noise ratios, and increase the requirement for data processing and calibration.

Temporal resolution is also limited by orbit characteristics (for satellites), flight duration (for aircraft), and weather conditions. Geostationary satellites make frequent (hourly or better) observations, but at low spatial resolution (km). Polar orbiting satellites vary considerably but usually range from several days to a month or more, depending on swath width and altitude. Aircraft are generally limited to less than 10 h for piloted and less than 30 h for unmanned aerial systems (UAS). Area coverage is also limited by the airspeed of the aircraft, making large areas difficult to survey at high repeat rates. Weather is a severe constraining factor for all optical measurements, but less so for observations in the microwave portion of the spectrum.

Thresholds are important. This is particularly true for the tradeoff between spectral and spatial resolution. Low spectral resolution (broad band) multispectral sensor systems provide data that are usually interpreted through statistical methods. Spectral "signatures" are developed by collecting numbers of pixels and calculating measures of central tendency for each map unit. The attempt is to collect enough information to characterize a map unit's spectral central tendency and variance. A good rule of thumb is to size the spatial resolution about an order of magnitude below the minimum mapping unit (e.g., ~30 m pixel for a 1 ha feature). High spectral resolution systems (hyperspectral) do not have this limitation. Sub-pixel analysis is made possible by looking for absorption features that match a spectral library at the molecular level. While there are limits, it is reasonable to expect detection of spectral features at 0.1 pixel (e.g., ~3 m pixel for a 1 m resource), especially for discrete (not intimate) mixtures. Oversampling in the spectral domain thus significantly reduces the need for oversampling in the spatial domain. Of course, water is a dark target and the hyperspectral instrument must have a high signal-to-noise ratio to be useful in the marine environment. Additionally, the author is unaware of any remote sensing-based spectral libraries for DFG, but plastics are likely to have significant features in the 0.4–2.8 μm region of the spectrum, where most hyperspectral systems operate, and Fourier Infrared Spectroscopy has been suggested as a laboratory technique (O'Keefe, 2004). The limitation is that reflected infrared energy only penetrates the water column a few millimeters, placing an emphasis on spectral features in the 0.4–0.7 μm range for subsurface features, where the remote sensing penetration depth can be approximately the Secchi depth, depending on wavelength.

Given that different systems are optimized for different stages of the tasks of detection and removal, a combined (multistage) approach often optimizes the solution at minimum cost (Colwell, 1975). This is analogous to the predator searching first for the habitat for prey and then for the prey itself, thereby ignoring unproductive geography and minimizing energy used. The use of a model (process knowledge) followed by wide area search (spatial stratification) and then intensified (direct) search optimizes the use of resources and increases the likelihood of success. In the case of DFG, models and indirect detection using satellite systems optimize the subsequent search with direct means. The direct detection stage then may use aircraft-based observations to direct the ship to the debris. The previous stages exist only to refine the search strata to a manageable area for aircraft systems to be effective. As mentioned above, the final search is not a sampling scheme, but rather the canvassing of a reduced area.

5. Actionable information

Derelict fishing gear items are in motion. Information on location and even sampling strata are ephemeral. While large features in the ocean are relatively stable, weather conditions can significantly change the distribution of parcels of water and currents can move materials over considerable distances. Thus, the final stages of stratification and search must be carried out over a relatively small time step. This is probably on the order of hours. For information to be actionable, telemetry and analysis must be near-real-time. This requires either broad band telemetry between the sensor system and the ship or significant on board processing on the remote sensing vehicle. A plausible augmenting system would also be an optical remote sensing system small enough to be carried on a vehicle that could be retrieved by the ship (such as a small helicopter or fixed wing UAS).

Weather is a critical factor for both detection and cleanup. Clouds obscure satellite imagery (except radar) and also reduce contrast for aircraft flying below them. Wind affects sea state, as well as currents, and impacts both cleanup and detection. Therefore, both stratification and direct detection must be coupled with the right sensor suite, timely data processing, communication facilities, and the right environmental conditions to produce actionable information. In extreme cases, this might limit effective operations to just a few days per month. Accurate and timely weather forecasting will also be essential to enhance the chance of success.

6. Sensor/platform tradeoff considerations

For optical satellite imagery to be useful in determining broad-scale features, temporal resolution must be daily. For example, the Moderate Resolution Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites provide twice-daily views of most of the earth. Routine ocean products produced include sea surface temperature, particulates, and chlorophyll *a*. These products characterize the broad-scale features of the ocean at coarse spatial resolution. Though sometimes problematic for Case II (coastal) waters, these appear to be ideal for mapping km-scale features in the open ocean, such as major convergent fronts. These products are often averaged over several days to obtain cloud-free products.

Optical aircraft-based systems include thermal and visible–near infrared systems. (For a more complete discussion of particular instrument candidates, see the companion article by Veenstra and Churnside, in press). They also include systems that are multispectral and hyperspectral. As discussed above, the multispectral data have requirements for very high spatial resolution in the

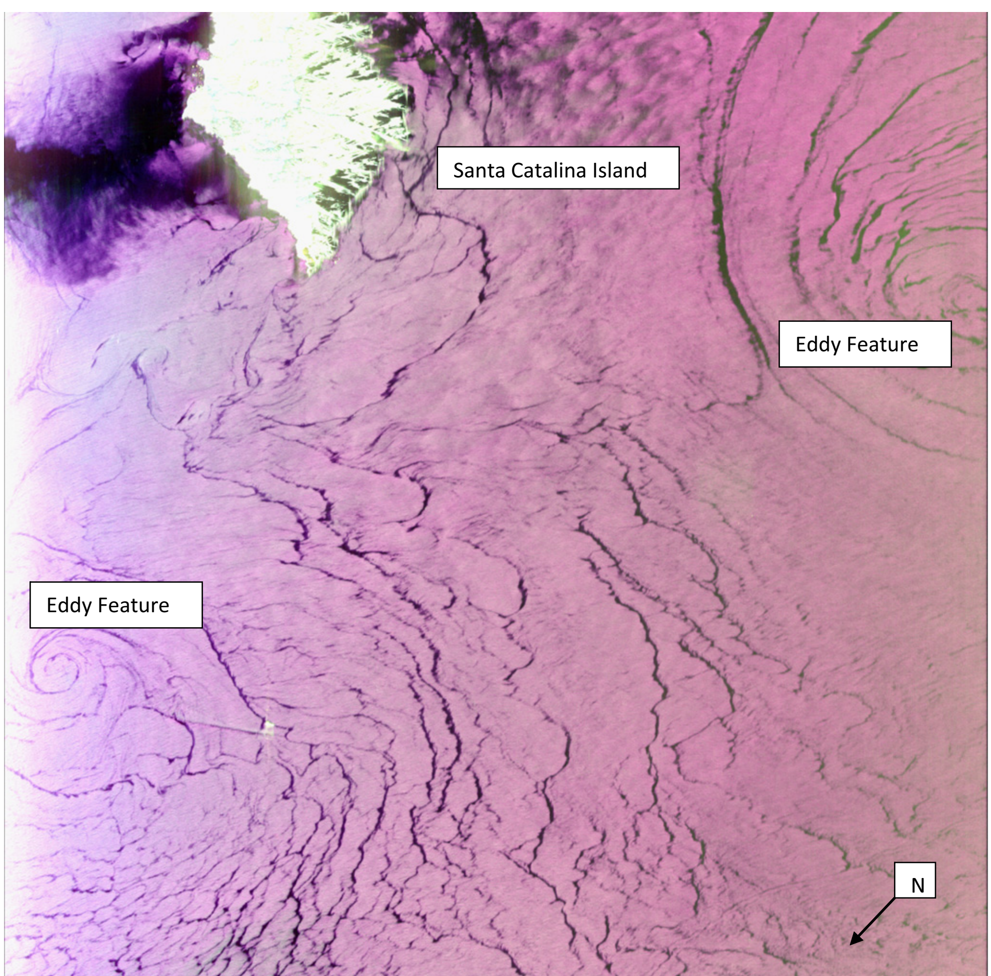

Fig. 1. UAVSAR polarimetric three-color composite image of fine-scale currents and eddies in the Santa Barbara Channel acquired on September 16, 2009, from the NASA G-III aircraft. The northernmost tip of Santa Catalina Island is shown for scale.

visible and near infrared to detect debris directly. This is probably impractical, except for small UAS cameras that extend the visual range of an observer from a ship. Thermal scanners may be useful, but are subject to limitations of cloud cover. An useful system might be the multispectral/thermal system flown on the Ikhana (Predator B) UAS for fire mapping. Based on the NASA Airborne Thematic Mapper Simulator and the Ocean Color Imager, this is a re-designed Daedalus 1268 multispectral scanner with interchangeable detector assemblies. While this system could not perform direct detection, it could use near real-time telemetry to broadcast indirect measurements to a ship. Cloud cover would remain a problem. Direct detection with a high-resolution hyperspectral system such as the Jet Propulsion Laboratory's Portable Remote Imaging Spectrometer (PRISM, http://hdl.handle.net/2014/41637) is theoretically possible, but would still need to be flown at a relatively low altitude and would have limited swath width.

Radar systems show great promise in delivering the detailed information needed to direct a cleanup action, especially in the presence of clouds. An excellent general overview of the use of radar for marine observations is provided in the NOAA-sponsored *Synthetic Aperture Radar Marine User's Manual* (Holt, 2004). Romeiser et al. (2005) further suggest that along-track interferometric satellite radar (InSAR) may be optimum for mapping surface currents. While satellite radars are becoming available routinely, the repeat passes are not optimum for mapping fine-scale features on the time step required for cleanup operations. It appears that aircraft-based systems are likely to be required to map the meso- to fine-scale features needed to direct a ship to the debris areas, even though they are unlikely to detect the debris directly.

New airborne radar systems are becoming available that may be good candidates for investigation. For example, observations of the Santa Barbara Channel by the NASA L-Band Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) in 2009 indicate that simple, polarimetric quick-look images from an on board processor may be useful to direct ships to eddy regions (Fig. 1). UAVSAR was designed to be flown on manned (Gulfstream III) and unmanned (Global Hawk) platforms (Fig. 2). The implementation on the Gulfstream III is operational, while the Global Hawk implementation is expected to be available in the future and could be as depicted or implemented as polarimetry only, with a single antenna and instrument mounted in the body of the fuselage. As implemented on the Gulfstream III, UAVSAR has limited telemetry and telepresence, a swath width of 20 km, and spatial resolution of approximately 2 m. It is flown above most weather at a GPS altitude of 41,000 ft (12.5 km). Mission duration is approximately 6 h, potentially covering up to 95,000 km^2, making it a good candidate for a feasibility study. The future Global Hawk implementation proposed for UAVSAR will have a mission duration of over 24 h from roughly the same altitude, making it a more appropriate platform for operational survey.

7. Future state

The United States and the international community have developed a vision for multistage remote sensing integrated into in situ monitoring systems called the Global Earth Observation System of Systems (GEOSS). The coordination for GEOSS is through the Group on Earth Observations (GEO). As defined on the group's web site: http://www.earthobservations.org/about_geo.shtml.

"GEO is a voluntary partnership of governments and international organizations. It provides a framework within which these partners can develop new projects and coordinate their strategies and investments. As of September 2009, GEO's members include 80 Governments and the European Commission. In addition, 56 intergovernmental, international, and regional organizations with a mandate in Earth observation or related issues have been recognized as Participating Organizations."

A similar vision for model results integrated with measurements from satellites, aircraft, and ships has been successfully implemented for DFG detection and tracking through the Ghost Net Project (Pichel et al., 2003). This project provides a solid base that is consistent with the principles of multistage remote sensing articulated by Colwell (1975) over three decades ago as well as with the international vision for the future of GEOSS. Refinement

Fig. 2. Artist's concept of the Global Hawk UAS with proposed dual antenna UAVSAR system installed.

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of the Ghost Net procedures could productively include a final search stage using airborne radar and telepresence from an UAS simulator aircraft to detect zones of potential accumulation and direct ship-based search. The search may also be improved by using a remotely piloted small helicopter, launched and recovered by the ship, to extend a visual search using nadir-viewing optical sensors and shipboard telemetry for direct detection of the debris. This augmentation would need to be tested, but could be easily done using existing systems as a proof of concept for using more automated systems in the future.

8. Conclusions and recommendations

At-sea detection and removal of DFG remains a serious challenge to current technology. Tradeoffs between costs and remote sensing resolution must be carefully made. Strata development will be critical in successful detection and cleanup. Using models, satellite radar and multispectral data, and airborne remote sensing, particularly radar, to focus the search on eddies and convergent fronts in the open ocean appears to be a productive avenue of investigation. The development of new airborne sensors and the corresponding development of unmanned aerial systems to carry them is generating new capabilities which may cross observation thresholds, enabling effective detection and cleanup of DFG at-sea. Presently, no remote sensing systems are likely to be able to directly detect marine debris when flown in survey mode (optimized for area coverage). The Ghost Net Project has developed, and successfully tested, procedures for using models, satellite observations, and aircraft to observe debris. Extending their procedures to use airborne radar as a final search stage, followed by visual detection from a small UAS, low altitude aircraft, or ship is the most likely refinement to be successful.

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