Quantifying and reducing uncertainty in UXO site characterization

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Published online: 16 January 2008
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Decades of military operations at bases and ranges within the US have left behind a legacy of unexploded ordnance (UXO). Estimates of the total land area that may be contaminated with UXO are as high as 4 million hectares (10 million acres) (Defense Science Board, 2003). This area is distributed over potentially thousands of individual sites. While these overall area estimates are large, in the majority of these sites, the UXO is expected to be concentrated in as little as 10% or less of the site area. Current cleanup costs of ranges containing UXO could exceed \$100 billion (US GAO 2004). Efficient characterization and remediation of these land areas is necessary before they can be released for other uses.

Rapid advances in sensor technology, signal processing and geo-location have been made over the past decade. These advances have initiated the era of digital geophysical surveying of land with potential UXO contamination. Arrays of magnetometers and/or electromagnetic sensors can now be mounted onto or towed behind vehicles to collect continuous surveys that provide the positions of geophysical anomalies. These developments have been guided by the US Department of Defense Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) offices.

While these developments have made it possible to geophysically survey tens to hundreds of acres of land per

day in some situations, a number of outstanding challenges still complicate UXO site characterization and remediation:

- (1) for any single geophysical survey, the probability of detection for subsurface objects is less than 1.0 and false alarm rates associated with the geophysical sensor can be significantly above zero. Detection and discrimination are unsolved problems in nearly all field situations; therefore, it is generally impossible to survey directly for UXO,
- (2) geophysical data are often collected in strip transects, typically hundreds of meters to kilometers in length, but only 2–8 m wide. Issues regarding the optimal placement of these strip transects for a given conceptual site model and proper analysis techniques for the data obtained along these transects present areas of research,
- (3) in a wide-area site characterization, target areas, regions of a site where the geophysical anomaly density is above the background density, can be indicative of areas where ordnance use was focused and identification and delineation of these areas from limited sample data is often a goal of the site characterization process. A number of factors influence the ability to identify target areas from the background anomaly density and different models of spatial point processes are being applied to this problem.
- (4) due to constraints on resources, it may only be possible to sample 1% or less of the entire site area with geophysical transects. Optimal means of extrapolating information from these transects across the site using spatial estimation/simulation techniques is an area of ongoing research. Additionally, the development and integration of secondary data streams

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(e.g., airborne imagery) into these spatial estimation/simulation procedures is being studied.

- (5) given the uncertainties inherent in site characterization and the detection and discrimination of individual UXO objects, the prioritization of geophysical anomalies for excavation and development of rules for the cessation of excavation after no UXO have been found and for verification that few if any UXO remain are areas of current research.

The papers in this special issue address a number of these research areas. The authors of these papers are drawn from the broad expertise of the science and technology community that is now focused on problems of UXO site characterization. This community is comprised of experts in a number of sub-disciplines across a range of technical backgrounds including geophysics, environmental engineering, statistics, electrical engineering, image processing, and others.

The papers in this special issue are arranged in the rough chronological order of the steps followed in a typical site characterization process from detection and discrimination issues of the individual geophysical sensor to design of geophysical transects for the initial site characterization, analysis and mapping of the data obtained in the geophysical surveys through design of post-remediation compliance sampling.

Two papers in this special issue address the general problem of discriminating UXO from other objects in the subsurface with electromagnetic sensors. Tatum et al. examine the impact of position error in the sensor on the ability to classify objects in the subsurface and highlight the need for accurate statistical models of position error to improve classification results. Benavides et al. propose self-organizing maps as an improved means of classifying subsurface objects from EM data and test the results on data from simulations as well as a field site.

The problem of transect sampling design with the goals of both traversing and identifying a target area as a region with a geophysical anomaly density significantly above the background density is addressed by Matzke et al. The simulation approach needed to determine the probability of target area detection is described and various aspects of the transect design and target area identification approaches are demonstrated on three different field sites.

McKenna presents a new approach to identifying target areas from geophysical anomaly data collected along strip transects. This paper uses hidden Markov models (HMM) and the anomaly density along a transect to classify each

transect into target and background regions. MacDonald and Small demonstrate that the spatial point pattern of geophysical anomalies can be used to discriminate between background and target areas on a site. Additionally, they show that the point patterns produced by both ground-based and airborne geophysical surveys are consistent.

The next three papers address different aspects of deriving spatially extensive estimates of the geophysical anomaly density from limited geophysical surveys with or without the addition of secondary information as obtained from airborne imagery. Ostrouchov et al., define three distinct scales in the site characterization process, that of the ordnance, the target areas and the site. They conceptualize the anomaly density distribution as being the result of a Cox process and then demonstrate estimation of anomaly density from limited transect data using kriging and a log-Gaussian model of the anomaly density. Roberts and McKenna address the problem of combining limited transect sampling of a site with spatially exhaustive estimates of crater density derived from airborne LiDAR imagery. The impact of different geostatistical algorithms used for this data fusion on the results is compared using a well-characterized site. Johnson et al. also examine the problem of preparing and integrating different data sets for the case of three full coverage data sets: LiDAR, orthophotography and airborne magnetometry.

Finally, the problem of post-remediation compliance sampling is addressed by Hathaway et al. The authors examine the sampling designs necessary for post-remediation compliance using a series of simulations that demonstrate the efficiency of different compliance sampling designs for varying degrees of clustering in the remaining anomaly locations.

We extend our deepest appreciation to the contributors of this special issue for the efforts they have made in producing the papers contained herein and also thank them and others for their timely efforts in reviewing the manuscripts.

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