



INSTITUTE FOR DEFENSE ANALYSES

**Assessing the Capability of Advanced  
Geophysical Classification Techniques to  
Inform Minimum Separation Distances for  
UXO Remediation (Briefing)**

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March 2020

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### **About This Publication**

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# Executive Summary

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## Introduction

From 2007 to 2017, the Environmental Security Technology Certification Program (ESTCP) sponsored a series of live-site demonstrations to assess the capabilities of newly developed advanced geophysical classification (AGC) technologies to detect and classify buried targets of interest (TOI) (unexploded ordnance (UXO), inert and surrogate munitions, seeds, and any other objects for which the site team agrees that removal is required). These technologies have been shown to detect TOI and reject clutter with a high probability of detection and correct classification and low probability of false alarm, saving the DoD in remediation costs. Previous IDA analyses summarized the capabilities of AGC to differentiate TOI from clutter. These analyses did not take the size of the detected objects into account. The capability to predict the size of a buried object could allow the DoD to more appropriately set the minimum safe distance (MSD) in UXO remediation projects, thus saving more in remediation costs. We have therefore conducted a retrospective analysis of the ESTCP live-site demonstrations in order to determine the capabilities of AGC to inform the MSD based on the predicted size of the detected objects.

## Results

For 104 Ranked Anomaly Lists (RALs) from 10 live-site demonstrations, IDA retrieved the actual and predicted sizes for every TOI. The sizes were binned into small ( $< 50$  mm diameter), medium ( $\geq 50$  mm and  $< 100$  mm), or large ( $\geq 100$  mm) categories. A confusion matrix was created for each RAL, and the numbers of TOI events in each category were assessed. In particular, attention was paid to the number of TOI events that were predicted to be in a smaller category than their actual size, as this type of error could inform a dangerously short MSD. We found that size predictions were correct for the majority (90%) of TOI, and when predictions were incorrect, they tended to err on the side of caution (predicted larger than reality 7% of the time). Only 3% of predictions were unsafe (predicted smaller than reality), and in only one instance out of 104 RALs was a large TOI predicted to be in a small size category.

## Conclusions

AGC technologies show evidence of being able to predict the size category of buried TOI. This capability could be used to help set the MSD in UXO remediation projects.





**Assessing the Capability of  
Advanced Geophysical Classification (AGC)  
to Inform  
Minimum Separation Distances (MSD)  
in Unexploded Ordnance (UXO) Remediation**

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March 31, 2020

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Fisher, K. and Cazares, S. (2020) Assessing the Capability of AGC to inform MSD in UXO Remediation. SAGEEP 2020, Denver CO, 3/29/20 – 4/2/20

This briefing was prepared in response to an invitation to speak at the 33<sup>rd</sup> Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) / 1<sup>st</sup> Munitions Response Meeting, planned for March 29 – April 2, 2020 in Denver, CO. The symposium did not take place due to the COVID-19 pandemic.

This briefing summarizes an assessment done by the Institute for Defense Analyses (IDA) regarding the capability of Advanced Geophysical Classification (AGC) to inform Minimum Separation Distances (MSD) in Unexploded Ordnance (UXO) remediation.

Millions of acres of land inside the continental United States are potentially contaminated with UXO. UXO refers to munitions that were previously armed and fired but did not explode—they were duds. They still pose a risk of detonation, though. The Department of Defense (DoD) retains liability for UXO even after the land is sold for private use. Therefore, the DoD has a vested interest in remediating this land of UXO—cleaning it up. UXO remediation is an expensive process. The Environmental Security Technology Certification Program (ESTCP) is a DoD organization tasked with lowering that cost while maintaining safety.

## Background

2007–2017: ESTCP sponsored a series of live-site demonstrations to assess the capability of **advanced geophysical classification (AGC)** for safely remediating land of unexploded ordnance (UXO) while reducing remediation costs



**UXO**

vs.



**Clutter**

ESTCP = Environmental Security Technology Certification Program

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For over 20 years, ESTCP has sponsored development of Advanced Geophysical Classification (AGC) technologies and processes. AGC technology consists of novel instruments and software that can detect buried objects and remotely classify them as UXO vs. Clutter.

- All UXO must be safely removed from the ground, since they pose a risk of detonation.
- Clutter refers to metallic objects that pose no risk of detonation. Examples are fragments of previously detonated munitions and other objects like pipes, barbed wire, pieces of plows, and so forth.

From 2007–2017, novel AGC instruments and software were tested at different demonstration sites that mimic real-life remediation projects. These were called “live sites”—sites that were potentially contaminated with real UXO, due to their prior use as military test sites or training camps. The purpose of these demonstrations was determine which instruments and software worked best and how best to use them.

## Background

- **Targets of Interest (TOI)** are UXO, inert and surrogate munitions (“seeds”), and any other objects for which the site team agrees that removal is required
- IDA’s previous analyses have shown that **AGC** can detect and correctly classify TOI vs. clutter with few to no misses while reducing false alarms
- Correctly predicting **TOI size** could inform the **Minimum Separation Distance (MSD)** (evacuation distance) set during remediation
  - AGC could help justify reducing the MSD, thus further reducing costs while maintaining safety
- IDA has now retrospectively analyzed the demonstration results to assess **how well AGC predicted the TOI size**
  - Using data from the early years of AGC, before quality control and accreditation processes (DAGCAP, QAPP, RCA/CA)

This is a success story. Based in large part on these live site demonstrations, the AGC technologies ultimately proved to be good at detecting UXO and classifying them vs. Clutter. Several instruments and software made it through the valley of death to market, where they are used today in remediation projects.

First, we must introduce a term: Target of Interest (TOI). TOI is the collective name for objects that must be removed from the ground. TOI includes UXO as well as inert and surrogate munitions (called “seeds”) that are purposely emplaced in the ground at a demonstration site in order to increase the sample size of TOI.

From 2007–2017, the live site demonstrations showed that AGC can detect and correctly classify TOI with very few false negatives (i.e., few missed TOIs). AGC can also reject clutter with an acceptable number of false alarms.

However, previous analyses focused on detecting buried objects and classifying them as TOI vs. Clutter. These analyses did not focus on how well AGC could predict the *size* of a TOI.

The reason this is important is that during a real-life remediation project, some UXO may detonate during the excavation and neutralization process. There are many factors that influence the size of the detonation, and one of the factors is the size of the object. Accurately predicting the size of the TOI before it is excavated would help inform a proper evacuation distance, or minimum separation distance (MSD).

This briefing focuses on IDA’s most recent analysis, in which we have re-examined the data from the live site demonstrations to assess how well AGC can predict TOI size. Keep in mind that these results refer to the early years of AGC development before formal quality control and accreditation processes came into use.

# Methods

Demonstrators collected and processed data at a demonstration site  
 Deliverable is a **Ranked Anomaly List (RAL)**

Target ID	Category	Dig Decision	TOI Size
XX-2003	Cannot Analyze	Excavate	Large
XX-2013	Cannot Analyze	Excavate	Large
XX-2030	Cannot Analyze	Excavate	Large
...	...	...	...
XX-2323	Training Set	Excavate	Large
XX-2338	Training Set	Excavate	Large
...	...	...	...
XX-2413	Likely TOI	Excavate	Large
XX-2504	Likely TOI	Excavate	Medium
XX-2665	Likely TOI	Excavate	Medium
XX-2503	Likely TOI	Excavate	Small
XX-2278	Likely TOI	Excavate	Large
...	...	...	...
XX-2677	Cannot Decide	Excavate	Medium
XX-2364	Cannot Decide	Excavate	Small
XX-2616	Cannot Decide	Excavate	Small
...	...	...	...
XX-2674	Likely Clutter	Leave Unexcavated	N/A
XX-2058	Likely Clutter	Leave Unexcavated	N/A
XX-2274	Likely Clutter	Leave Unexcavated	N/A
XX-2054	Likely Clutter	Leave Unexcavated	N/A
XX-2541	Likely Clutter	Leave Unexcavated	N/A
...	...	...	...

} Dig  
} Dig threshold  
} Do not Dig

TOI Likelihood Rank ↑



Demonstrators used AGC technology (instrument and software) at a live site. This photograph shows one of the authors of this briefing using a TEMTADS instrument during a demonstration. Demonstrators used instruments like this to collect data over the test site. Then, they use software to process the collected data in order to detect metallic objects buried in the ground. Next, they classify each detected object as TOI vs Clutter. Their deliverable is a Ranked Anomaly List (RAL). Each row of the RAL contains information regarding one detected object, including a metric related to the likelihood that the object is a TOI and, if they believe the object is a TOI, what they estimate its size to be.

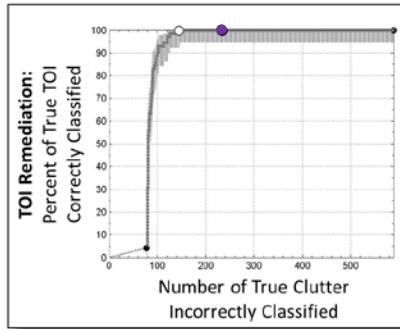
Separately, ESTCP had all detected objects excavated and catalogued after the demonstration– IDA scored each RAL against this ground truth information.

## Methods

Demonstrators collected and processed data at a demonstration site  
 Deliverable is a **Ranked Anomaly List (RAL)**

**Previous Analysis:**  
 TOI vs. Clutter

**ROC Curve**



Target ID	Category	Dig Decision	TOI Size
XX-200	Cannot Analyze	Excavate	Large
XX-201	Cannot Analyze	Excavate	Large
XX-203	Cannot Analyze	Excavate	Large
...	...	...	...
XX-232	Training Set	Excavate	Large
XX-233	Training Set	Excavate	Large
...	...	...	...
XX-241	Likely TOI	Excavate	Large
XX-250	Likely TOI	Excavate	Medium
XX-266	Likely TOI	Excavate	Medium
XX-250	Likely TOI	Excavate	Small
XX-227	Likely TOI	Excavate	Large
...	...	...	...
XX-267	Cannot Decide	Excavate	Medium
XX-236	Cannot Decide	Excavate	Small
XX-261	Cannot Decide	Excavate	Small
...	...	...	...
XX-267	Likely Clutter	Leave Unexcavated	N/A
XX-205	Likely Clutter	Leave Unexcavated	N/A
XX-227	Likely Clutter	Leave Unexcavated	N/A
XX-205	Likely Clutter	Leave Unexcavated	N/A
XX-254	Likely Clutter	Leave Unexcavated	N/A
...	...	...	...



In IDA's previous analyses, we looked at two columns of information on each RAL: the demonstrator's categorizations (TOI vs. clutter) and dig decisions (excavate vs. leave in place). Comparing this information to the true type of each object allowed us to construct a plot similar to a Receiver-Operating Characteristic (ROC) curve, which is a way of visualizing safety vs. cost tradeoffs of classification technology. The horizontal axis is false alarms and the vertical axis is related to TOI misses.

# Methods

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XX-2054	Likely Clutter	Leave Unexcavated	N/A
XX-2541	Likely Clutter	Leave Unexcavated	N/A
...	...	...	...

**Current Analysis:**  
TOI Size

### Confusion Matrix

		Analyst's Type				Total
		Non-TOI	Small TOI	Medium TOI	Large TOI	
Ground Truth	Non-TOI	372	4	144	17	537
	Small TOI	0	0	0	0	0
	Medium TOI	2	0	10	2	14
	Large TOI	2	0	2	33	37
	Total	376	4	156	52	588

In *this* analysis, however, we looked at the data in a different way. We focused on a different column of the RAL: the demonstrators' size predictions for TOI. These data had been collected but not analyzed before.

## Methods

- Each TOI at each demonstration site was assigned a size label of **Small, Medium, or Large** based on its **caliber or diameter**
- Tallies were made for the number of TOI size predictions that **matched**, were **larger than**, and were **smaller than** ground truth

Size	Caliber or Diameter (mm)
Small	<50
Medium	>=50 and <100
Large	>=100

		Analyst's Type				Total
		Non-TOI	Small TOI	Medium TOI	Large TOI	
Ground Truth	Non-TOI	372	4	144	17	537
	Small TOI	0	0	0	0	0
	Medium TOI	2	0	10	2	14
	Large TOI	2	0	2	33	37
	Total	376	4	156	52	588

□ = TOI events

To perform our analysis, we classified TOIs into size bins: small, medium, or large. Small objects were less than 50mm in diameter, and large objects were larger than 100mm.

Then, since we knew the demonstrator's TOI size predictions and the ground truth, we could construct confusion matrixes like on the right.

For example, consider the red "2" near the bottom of the confusion matrix. This means that there were two TOI events that were truly large, but were predicted to be medium by this particular demonstrator.

We condensed the nine TOI Event boxes outlined in the blue square into three different groups, keeping track of how correct the size predictions were. We have color-coded them, and we will use these colors throughout the remainder of this briefing:

- Green means that the size predictions were correct, such that a MSD (evacuation distance) based on the predictions would have been appropriate.
- Yellow means that the size prediction was wrong, but in a safe direction: the objects were predicted to be larger than they actually were, such that a MSD would have been too large. Although this error was cautious, it would have led to more costs than needed—for example, more residents might have been evacuated than needed.
- Red means that the size prediction was wrong, but in a potentially unsafe direction, as described on the next slide.

## Methods

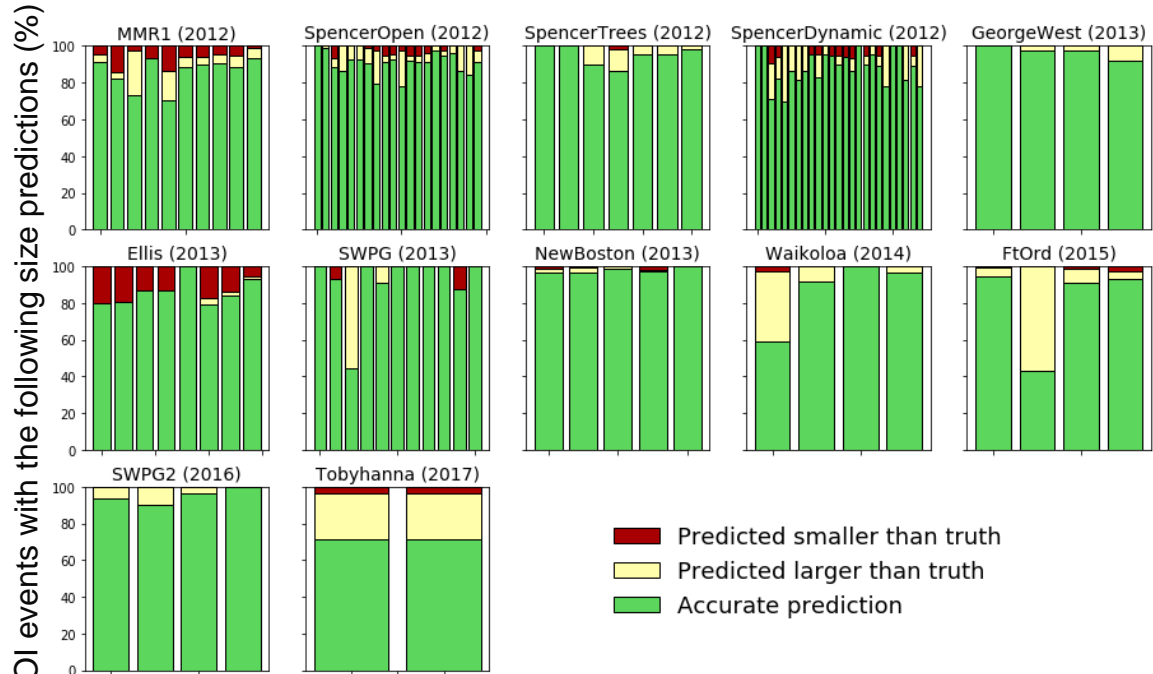
TOI size predictions that were smaller than ground truth were assessed in more detail, since these **too-small predictions would have informed a too-short MSD** in a real-world UXO remediation project

		Analyst's Type				Total
		Non-TOI	Small TOI	Medium TOI	Large TOI	
Ground Truth	Non-TOI	372	4	144	17	537
	Small TOI	0	0	0	0	0
	Medium TOI	2	0	10	2	14
	Large TOI	2	0	2	33	37
	Total	376	4	156	52	588

The incorrect predictions that we are most concerned about are the red ones. Red squares mean that the size prediction was wrong in a potentially unsafe direction: the objects were predicted to be smaller than they actually were, such that a MSD based on these predictions would have been too short—for example, fewer residents would have been evacuated than needed. Note that this is only one confusion matrix representing the TOI size prediction capability of only one Ranked Anomaly List (RAL) from one live-site demonstration. In the following slide, we pool results from all RALs across all demonstrations.

# Results

TOI Size Prediction Performance of 104 Ranked Anomaly Lists submitted from 12 demonstration sub-sites:



- Each plot corresponds to one demonstration subsite
- Each bar corresponds to one Ranked Anomaly List submitted from that subsite
- Colors/shadings refer to the percentage of TOI events on that Ranked Anomaly List with **correct**, **too-small**, and **too-large** size predictions.

Individual RALs

Here we show the full results of our analysis. The bullet points describe the plots.

For example, the very last plot (bottom row, second column) refers to the results of the live-site demonstration at Tobyhanna Army Depot, PA. In this demonstration, there were only two RALs submitted (leading to two bars in the plot):

- About three quarters of the size predictions were correct (green).
- Another quarter were wrong but safe (yellow).
- A few predictions were wrong but potentially unsafe (red).

The two demonstrators also performed about equally well as each other.

Overall, there is a lot of green in these plots, indicating that most size predictions were correct. That is good.

Also, the number of yellow (safe) errors outnumber the red (potentially unsafe) errors. That is also good. When the size predictions were wrong, they tended to err on the side of caution.

## Results

### Overall unweighted averages:

- 89.85% (5,065/5,637) of TOI size predictions matched ground truth
- 7.38% (416/5,637) of TOI size predictions were larger than ground truth
- 2.77% (156/5,637) of TOI size predictions were smaller than ground truth

Combining data from all 12 demonstration sub-sites, the overall numbers show that approximately 90% of the size predictions are correct (green). 7% of predictions are larger than truth, erring on the side of caution (yellow) and just under 3% are smaller than truth, potentially unsafe (red).

The confidence intervals surrounding these percentages are:

- 89.04 – 90.61% green
- 6.73 – 8.09% yellow
- 2.37 – 3.23% red

assuming a binomial distribution and 95% certainty.

(source: <https://epitools.ausvet.com.au/ciproportion>)

## Results

When the size predictions were too small, how wrong were they?

### Overall unweighted averages:

- 89.85% (5,065/5,637) of TOI size predictions matched ground truth
- 7.38% (416/5,637) of TOI size predictions were larger than ground truth
- 2.77% (156/5,637) of TOI size predictions were smaller than ground truth

### TOI sizes predicted **smaller than ground truth**:

Ground truth	Prediction	Number
Large	Small	1
Large	Medium	67
Medium	Small	88
<b>TOTAL</b>		<b>156</b>

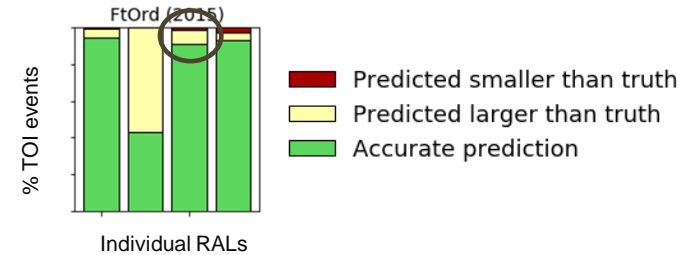
We then further examined the red predictions– these are the most concerning errors, even if there are relatively few of them.

Our first question was: when the predictions were wrong in a potentially unsafe way, how wrong were they?

It turns out that, in the entire decade’s worth of over five thousand TOI size predictions, only one TOI size prediction was wrong by two size categories: a large object that was predicted to be small.

## Results

0.02% (1 / 5,637) TOI events involved truly large TOIs predicted to be small



### Overall unweighted averages:

- 89.85% (5,065/5,637) of TOI size predictions matched ground truth
- 7.38% (416/5,637) of TOI size predictions were larger than ground truth
- 2.77% (156/5,637) of TOI size predictions were smaller than ground truth

### TOI sizes predicted **smaller than ground truth**:

Ground truth	Prediction	Number
<b>Large</b>	<b>Small</b>	<b>1*</b>
Large	Medium	67
Medium	Small	88
<b>TOTAL</b>		<b>156</b>

\*This object was a 155-mm projectile at 52-cm burial depth, analyzed by a **remediation company new to AGC**. All other demonstrators accurately predicted the size of this TOI.

**In retrospect, more training or better QC may have avoided this error**

This TOI size prediction involved a very large TOI (155 mm projectile) that was buried rather deep (52 cm). Furthermore, this particular TOI size prediction was made by a company that was new to AGC—in fact, this was their first time using AGC in a demonstration at this scale. More importantly, the size of this TOI was correctly predicted by the three other demonstrators at the site. In retrospect, more training or better quality control may have avoided this error.

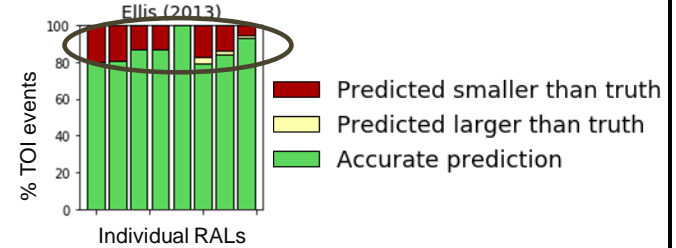
The confidence intervals (assuming a binomial distribution and 95% certainty) are: 0.00 – 0.10% (zero to one-tenth of a percent) of TOI events were truly large TOIs that were predicted to be small (source: <https://epitools.ausvet.com.au/ciproportion>).

## Results

What happened at Ellis?

### Overall unweighted averages:

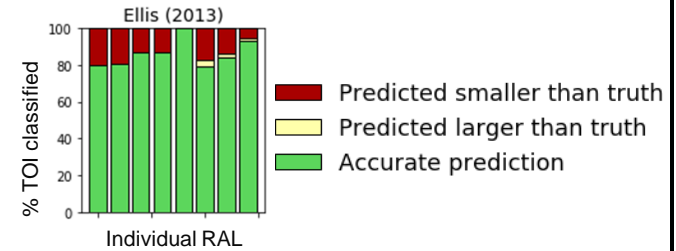
- 89.85% (5,065/5,637) of TOI size predictions matched ground truth
- 7.38% (416/5,637) of TOI size predictions were larger than ground truth
- 2.77% (156/5,637) of TOI size predictions were smaller than ground truth



You may recall from slide 8 that there was one demonstration that had more red errors than others. This was the demonstration at the former Camp Ellis, IL. We further examined these errors, as well.

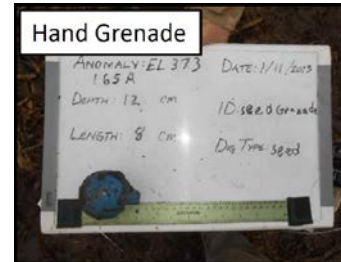
## Results

1.56% (88 / 5,637) TOI events involved truly medium TOIs predicted to be small. 36 of these 88 were **grenades, all at Ellis.**



### Overall unweighted averages:

- 89.85% (5,065/5,637) of TOI size predictions matched ground truth
- 7.38% (416/5,637) of TOI size predictions were larger than ground truth
- 2.77% (156/5,637) of TOI size predictions were smaller than ground truth



Ground truth labels were assigned based on TOI diameter, not overall TOI size

In retrospect, grenades could have been assigned a ground truth label of “small” due to their overall size, thus improving scores

It turns out that of the 156 red (potentially unsafe) prediction errors over all demonstrations, 88 involved truly medium TOIs that were predicted to be small. 36 of these 88 predictions were grenades, and all of them were at Ellis.

Recall that our ground truth size bins were set based on the object diameters. Here, we show two grenades, which are 60mm in diameter, above two rockets which are also 60mm in diameter. Although the grenades are much smaller in volume than the rockets, they are considered to be the same size according to our ground truth size bins.

In retrospect, grenades could have been assigned a ground truth label of small due to their overall size. That is, it's not that the predictions were wrong, but the ground truth size bins were. Adjusting the ground truth labels of grenades from medium to small would have improved scores. However, we decided to stick with our original ground truth size bin definition for consistency's sake.

## Discussion

- **AGC has demonstrated the capability to predict the size bin (small vs. medium vs. large) of a buried TOI in most cases. TOI size prediction could inform the MSD in UXO remediation:**
  - **≈90%** (5,065 / 5,637) of TOI size predictions matched ground truth and would have informed an appropriate MSD
  - **≈7%** (416 / 5,637) of TOI size predictions were larger than ground truth and would have informed a too-long MSD (erring on the side of caution)
  - **≈3%** (156 / 5,637) of TOI size predictions were smaller than ground truth and would have informed a too-short MSD
    - Only 1 large TOI was predicted to be small: a 155-mm projectile at 52-cm burial depth, analyzed by a remediation company that was new to AGC. More training may have improved their performance
    - 88 TOI events involved truly medium TOIs predicted to be small. 36 of these were grenades. Assigning ground truth labels based on overall size, rather than diameter, would have improved scores
- **It is likely that TOI size prediction performance may improve further due to quality control and accreditation processes implemented after these demonstrations took place (DAGCAP, QAPP, RCA/CA, etc.)**

## Future work

- More formally address the statistical dependence between multiple TOI events based on the same individual TOI.  
All RALs from the same demonstration contain (at least some of) the same TOI as each other
- Conduct a more detailed analysis of the sizes of TOI misses (if any) and false alarms in TOI vs. clutter classification
- Consider more specific TOI **type** predictions  
e.g. “hand grenade” instead of “small”

## Questions?

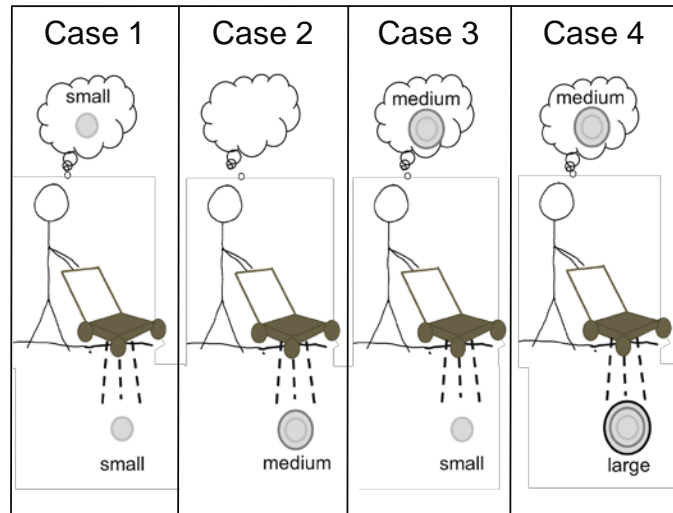
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## Methods (Backup)



<i>TOI vs. clutter classification</i>	<i>TOI Detected &amp; Correctly Classified</i>	<i>TOI NOT Detected or NOT Correctly Classified</i>	<i>TOI Detected &amp; Correctly Classified</i>	<i>TOI Detected &amp; Correctly Classified</i>	} ROC curves
TOI size prediction	correct	---	too large	too small	
informing MSD	appropriate	---	too long	too short	} Confusion matrices

# REPORT DOCUMENTATION PAGE

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14. ABSTRACT Introduction: From 2007 to 2017, the Environmental Security Technology Certification Program (ESTCP) sponsored a series of live-site demonstrations to assess the capabilities of newly developed advanced geophysical classification (AGC) technologies to detect and classify buried targets of interest (TOI) (unexploded ordnance (UXO), inert and surrogate munitions, seeds, and any other objects for which the site team agrees that removal is required). These technologies have been shown to detect TOI and reject clutter with a high probability of detection and correct classification and low probability of false alarm, saving the DoD in remediation costs. Previous IDA analyses summarized the capabilities of AGC to differentiate TOI from clutter. These analyses did not take the size of the detected objects into account. The capability to predict the size of a buried object could allow the DoD to more appropriately set the minimum safe distance (MSD) in UXO remediation projects, thus saving more in remediation costs. We have therefore conducted a retrospective analysis of the ESTCP live-site demonstrations in order to determine the capabilities of AGC to inform the MSD based on the predicted size of the detected objects. Results: For 104 Ranked Anomaly Lists (RALs) from 10 live-site demonstrations, IDA retrieved the actual and predicted sizes for every TOI. The sizes were binned into small (< 50 mm diameter), medium (>= 50 mm and < 100 mm), or large (>= 100 mm) categories. A confusion matrix was created for each RAL, and the numbers of TOI events in each category were assessed. In particular, attention was paid to the number of TOI events that were predicted to be in a smaller category than their actual size, as this type of error could inform a dangerously short MSD. We found that size predictions were correct for the majority (90%) of TOI, and when predictions were incorrect, they tended to err on the side of caution (predicted larger than reality 7% of the time). Only 3% of predictions were unsafe (predicted smaller than reality), and in only one instance out of 104 RALs was a large TOI predicted to be in a small size category. Conclusions: AGC technologies show evidence of being able to predict the size category of buried TOI. This capability could be used to help set the MSD in UXO remediation projects.					
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