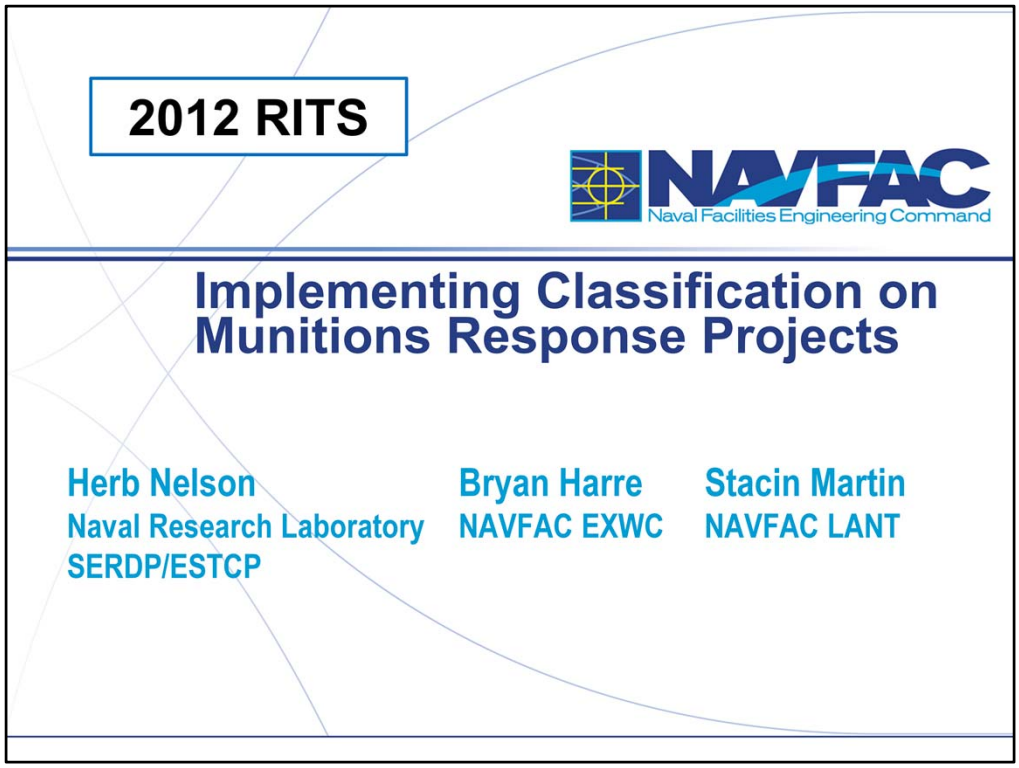
Using Classification Capable Sensors on Munitions Response Projects

Herb Nelson
Naval Research Laboratory
SERDP/ESTCP

Classification Applied to Munitions Response

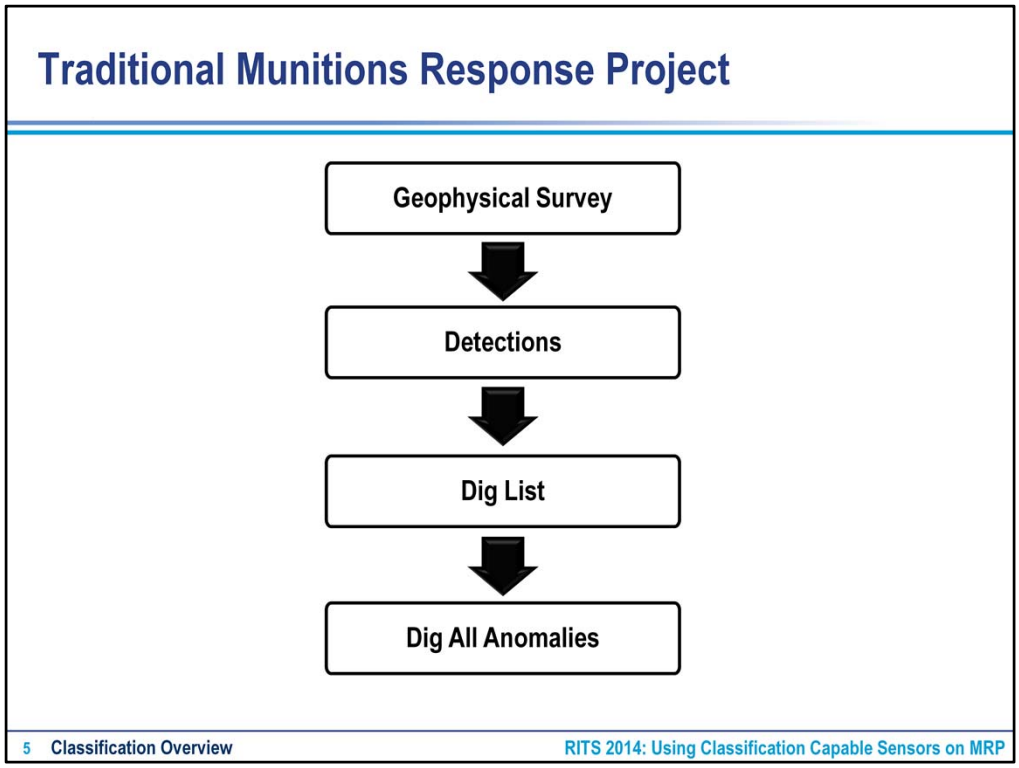
Just Because They're Making You Adopt This Doesn't Mean It's A Bad Idea

- **These methods reduce costs, damage, and disruption**
- **Better, richer data sets**
- **Change in procedures gives us an opportunity to sharpen our QC efforts**
- **But – not all parts of this make sense at all sites**


2012 RITS
NAVFAC
Naval Facilities Engineering Command
Implementing Classification on Munitions Response Projects
Herb Nelson
Naval Research Laboratory
SERDP/ESTCP
Bryan Harre
NAVFAC EXWC
Stacin Martin
NAVFAC LANT

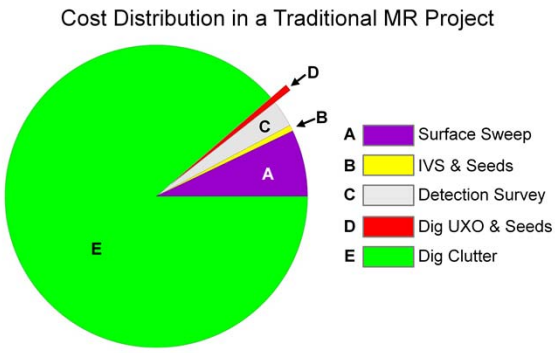
Presentation Overview

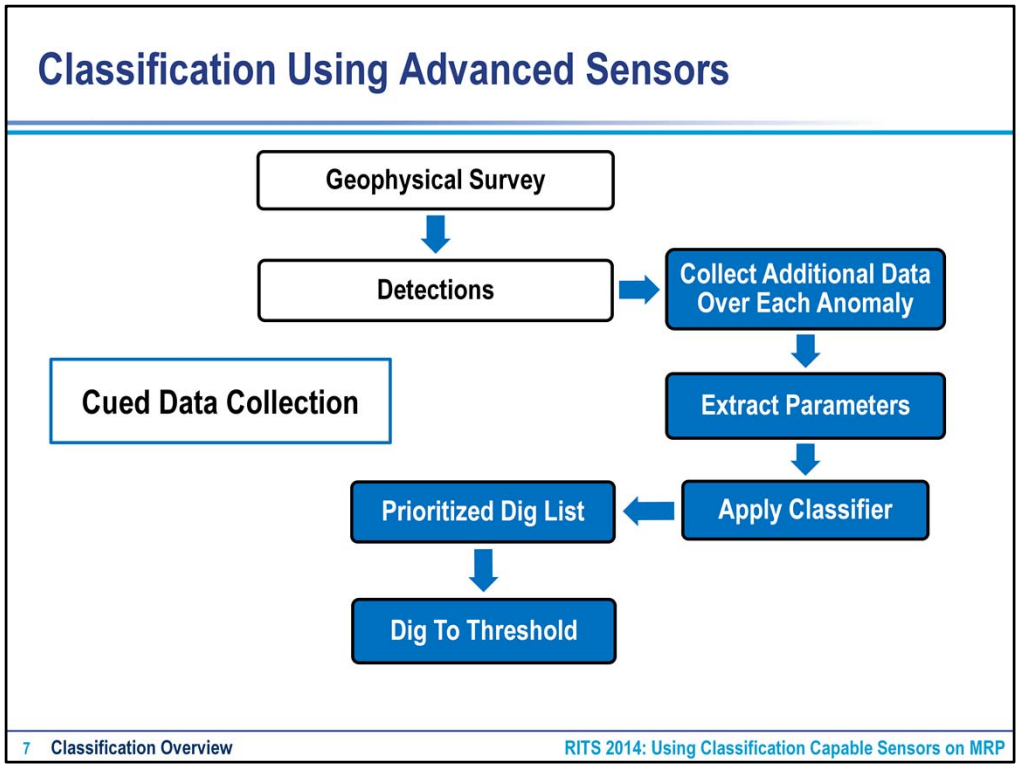
- Classification Overview
- Classification Basics
- Lessons from the ESTCP Demonstrations
- Update on Sensors, Deployment, and Data Analysis
- QC/QA Considerations
- Example Project
- Wrap Up

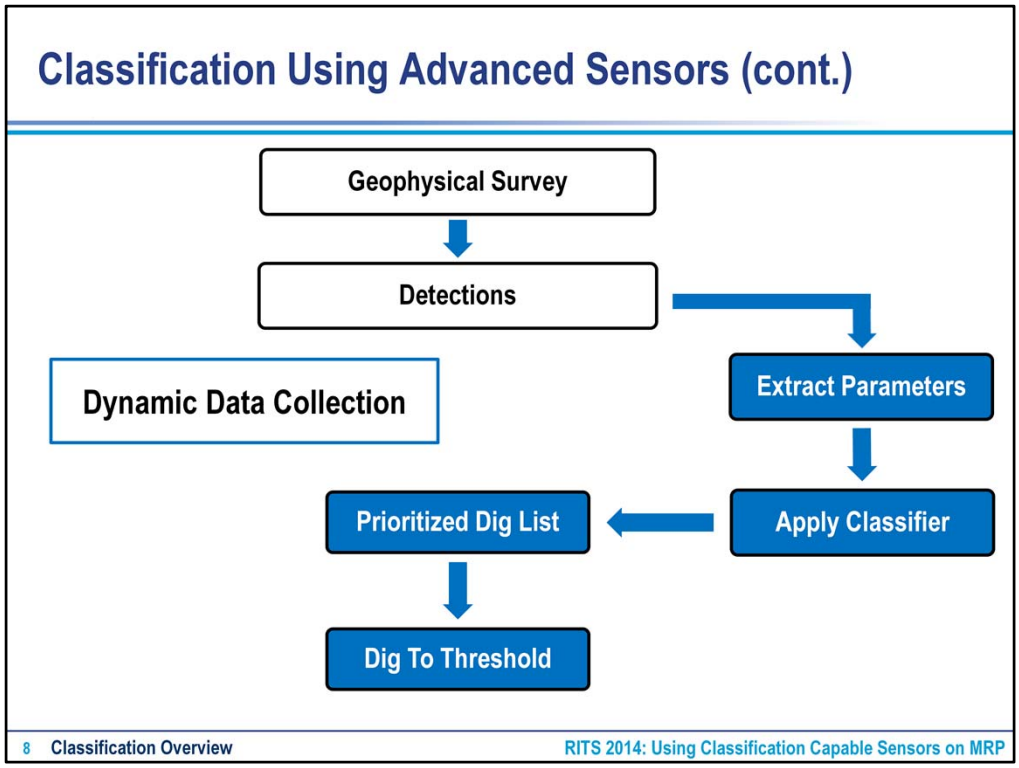

Traditional Munitions Response Project
Geophysical Survey
Detections
Dig List
Dig All Anomalies
5 Classification Overview
RITS 2014: Using Classification Capable Sensors on MRP

Costs Are Dominated By Digging Scrap

- Often <1% are UXO
- Example: Camp Butner, NC
  - 146 UXO out of >500,000 digs
  - Only 0.03% are UXO!




Classification Using Advanced Sensors
Geophysical Survey
Detections
Collect Additional Data Over Each Anomaly
Cued Data Collection
Extract Parameters
Prioritized Dig List
Apply Classifier
Dig To Threshold
7 Classification Overview
RITS 2014: Using Classification Capable Sensors on MRP


Classification Using Advanced Sensors (cont.)
Geophysical Survey
Detections
Dynamic Data Collection
Extract Parameters
Apply Classifier
Prioritized Dig List
Dig To Threshold
8 Classification Overview
RITS 2014: Using Classification Capable Sensors on MRP

Classification Applied to Munitions Response

Courtesy ESTCP

- Sort buried metal into two classes
- Because we cannot see buried objects, we must rely on attributes determined from geophysical data

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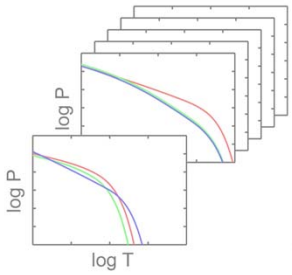
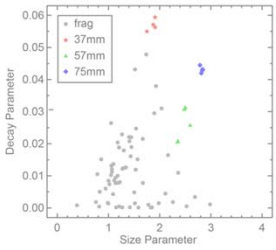
Stages in the Classification Process

Courtesy G&G Sciences

1. Measure target responses with suitable sensor
   - Classification-specific EMI



2. Extract target features from the measured responses
   - Data Inversion
   - Target polarizabilities

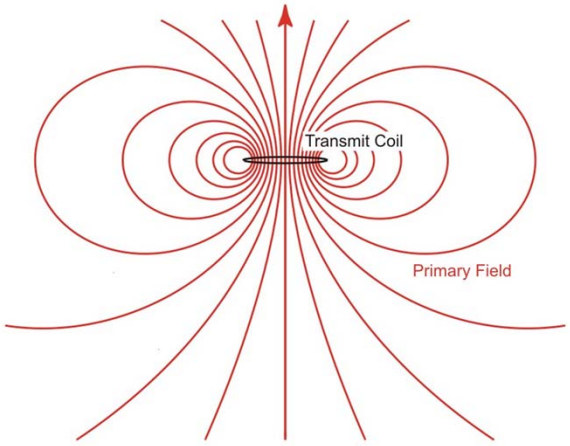


3. Classify targets based on the features
   - Statistical classifiers
   - Library matching

11 Classification Basics RITS 2014: Using Classification Capable Sensors on MRP

Electromagnetic Induction Sensors

Typical Electromagnetic Induction Sensor

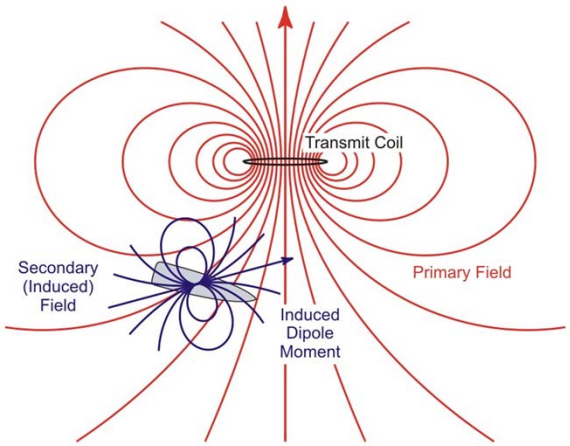


Excitation Pulse

12 Classification Basics RITS 2014: Using Classification Capable Sensors on MRP

Electromagnetic Induction Sensors (cont.)

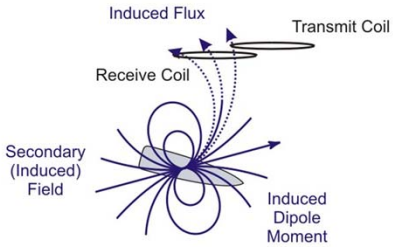
Typical Electromagnetic Induction Sensor



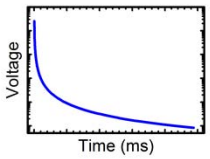
Induced Target Response

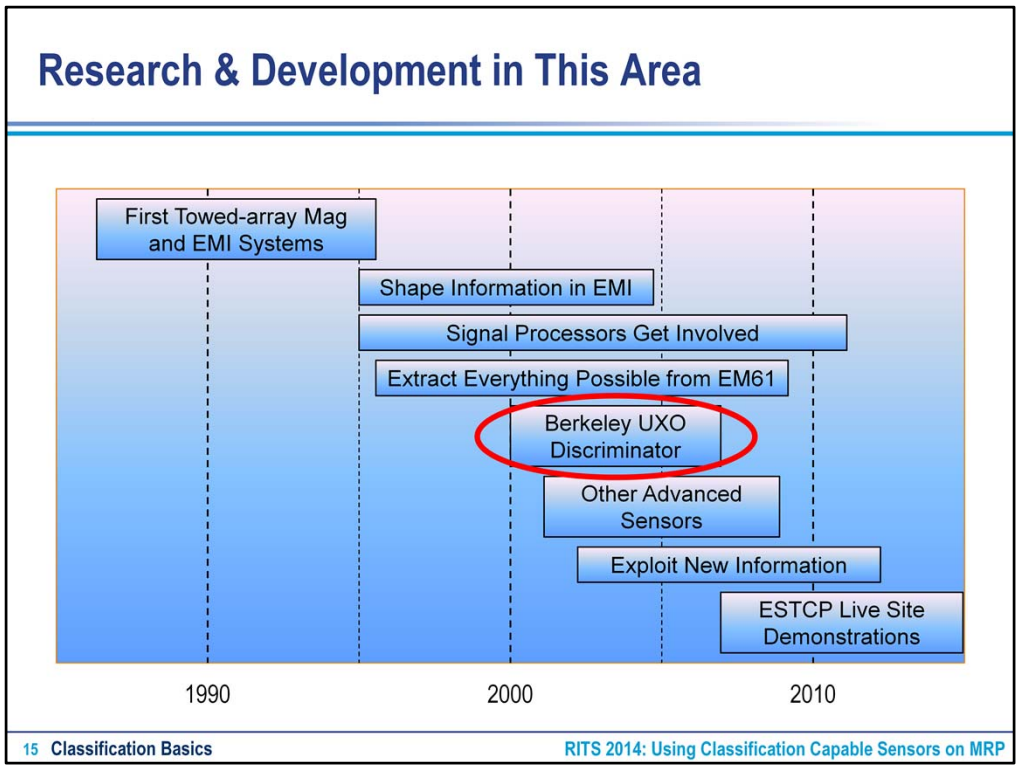
Electromagnetic Induction Sensors (cont.)

Typical Electromagnetic Induction Sensor

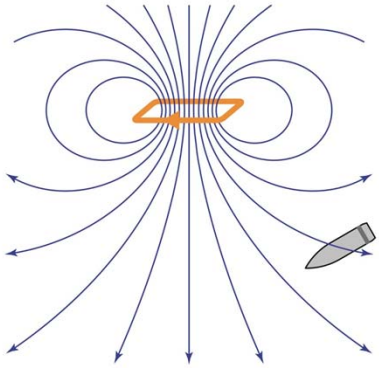


Sense Induced Field




Research & Development in This Area
First Towed-array Mag and EMI Systems
Shape Information in EMI
Signal Processors Get Involved
Extract Everything Possible from EM61
Berkeley UXO Discriminator
Other Advanced Sensors
Exploit New Information
ESTCP Live Site Demonstrations
1990
2000
2010
15 Classification Basics
RITS 2014: Using Classification Capable Sensors on MRP

Multiple Measurements are Required to Completely Characterize a Target with a Single-Axis Sensor

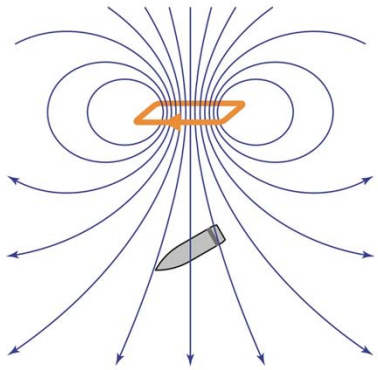


Courtesy Leidos

At each position the field lines only intersect the target in one direction

16 Classification Basics RITS 2014: Using Classification Capable Sensors on MRP

Multiple Measurements are Required to Completely Characterize a Target with a Single-Axis Sensor (cont.)



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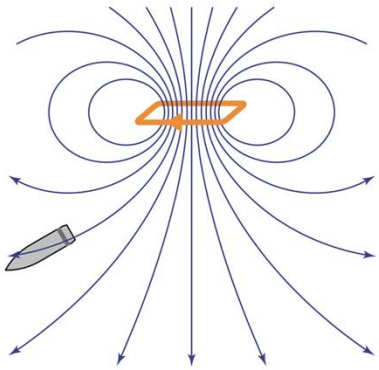
Multiple Measurements are Required to Completely Characterize a Target with a Single-Axis Sensor (cont.)



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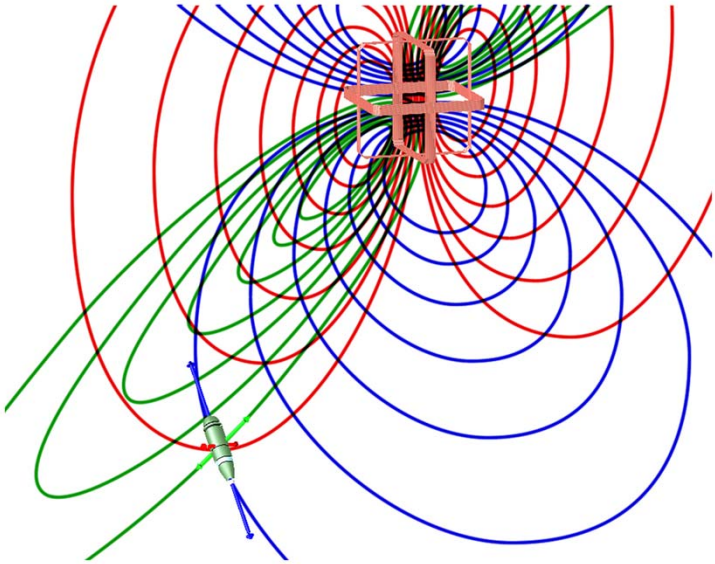
At each position the field lines only intersect the target in one direction

18 Classification Basics RITS 2014: Using Classification Capable Sensors on MRP

Advantages of a Multi-Axis Sensor



Advanced EMI Sensors

- New UXO-specific EMI technologies developed and tested under SERDP & ESTCP
- All digital electronics, measuring complete eddy current decay cycle
- Multi-axis, multi-coil data more completely defines target parameters

Courtesy ESTCP

Courtesy NOVA Research, Inc.

Courtesy Sky Research, Inc.

Advanced EMI Sensors (cont.)

- New UXO-specific EMI technologies developed and tested under SERDP & ESTCP
- All digital electronics, measuring complete eddy current decay cycle
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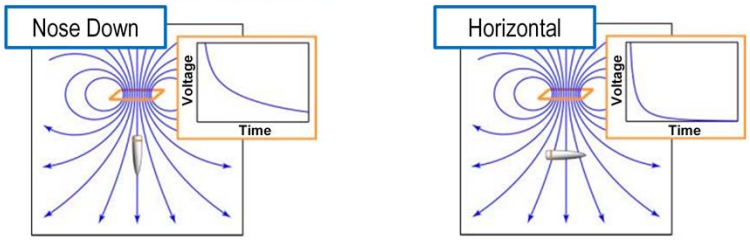
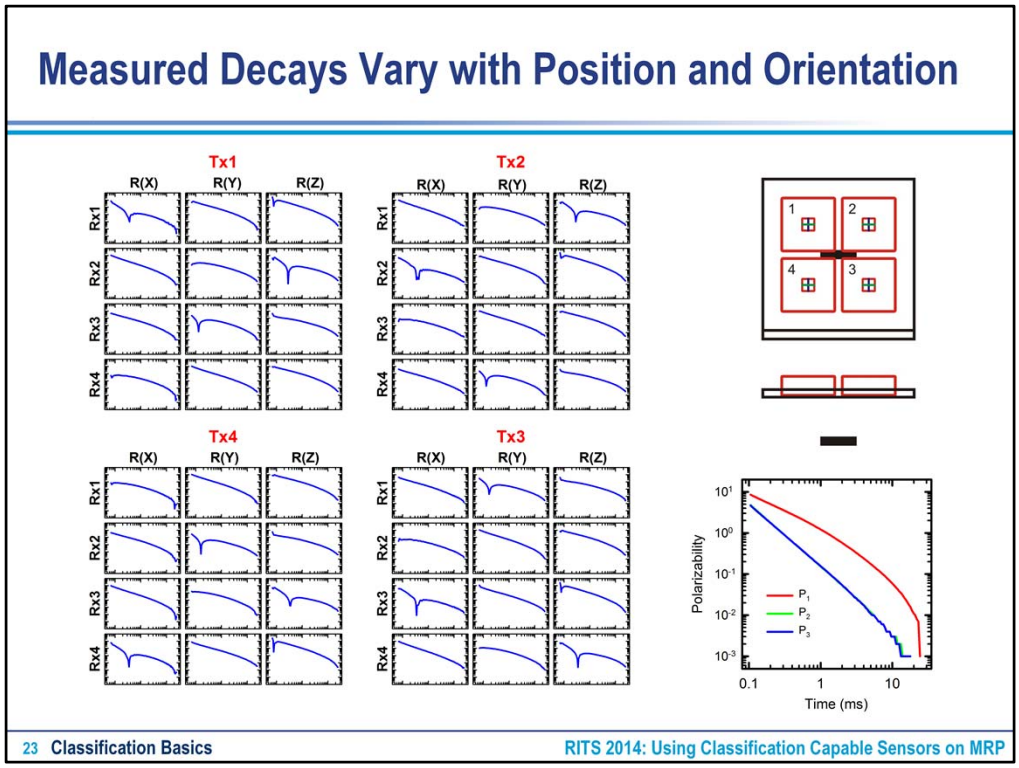
Photos courtesy California DTSC

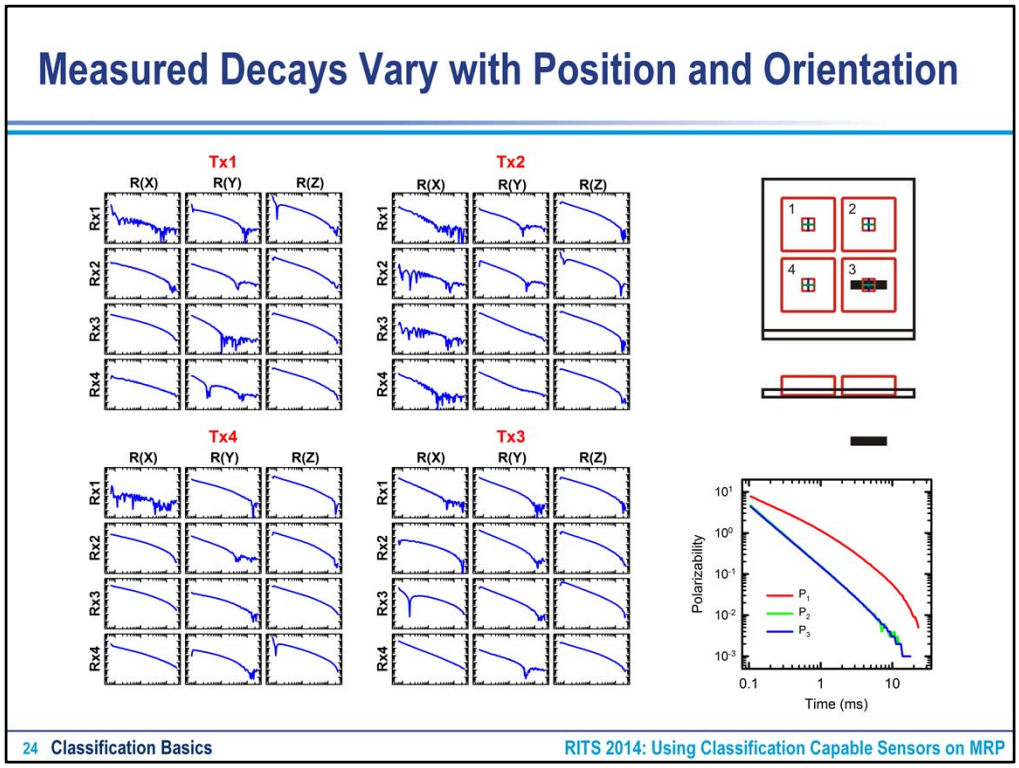
EMI Signals

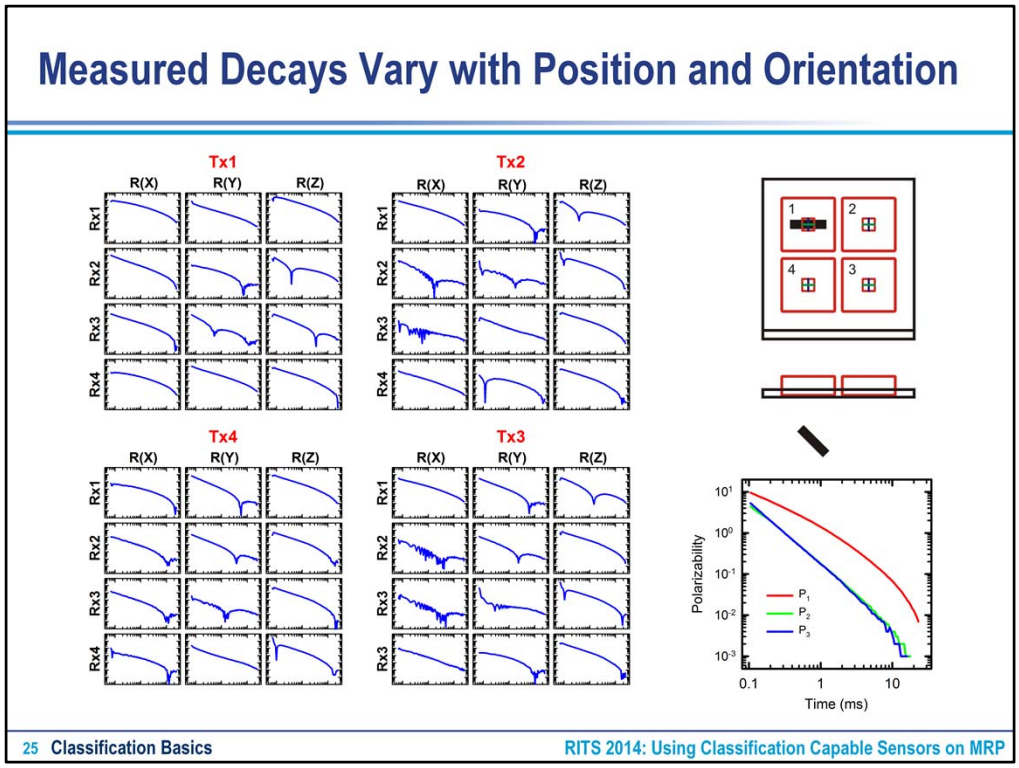
- EMI response signal determined by target properties
  - Size and Shape
  - Material type and thickness



- Muddled by response variation with target location and orientation relative to primary field
  - Signal strength varies as sixth power of range


Measured Decays Vary with Position and Orientation
Tx1
Tx2
Tx4
Tx3
R(X)
R(Y)
R(Z)
Rx1
Rx2
Rx3
Rx4
1
2
3
4
Polarizability
Time (ms)
P1
P2
P3
23 Classification Basics
RITS 2014: Using Classification Capable Sensors on MRP


Measured Decays Vary with Position and Orientation
Tx1
Tx2
Tx4
Tx3
R(X)
R(Y)
R(Z)
Rx1
Rx2
Rx3
Rx4
1
2
3
4
Polarizability
Time (ms)
P1
P2
P3
24 Classification Basics
RITS 2014: Using Classification Capable Sensors on MRP


Measured Decays Vary with Position and Orientation
Tx1
Tx2
Tx4
Tx3
R(X)
R(Y)
R(Z)
Rx1
Rx2
Rx3
Rx4
Polarizability
Time (ms)
P1
P2
P3
25 Classification Basics
RITS 2014: Using Classification Capable Sensors on MRP

Stages in the Classification Process

Courtesy G&G Sciences

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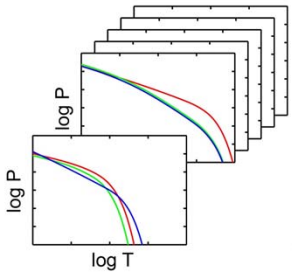

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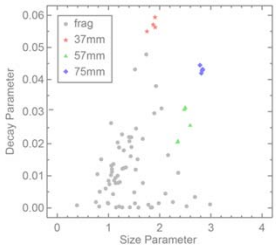

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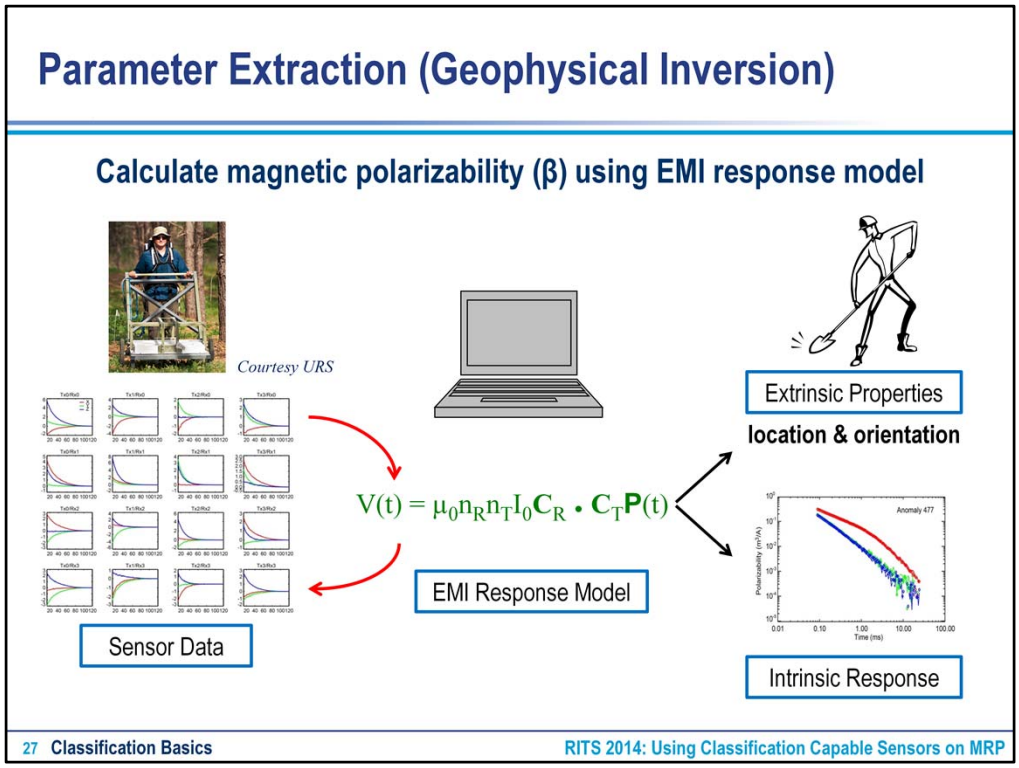
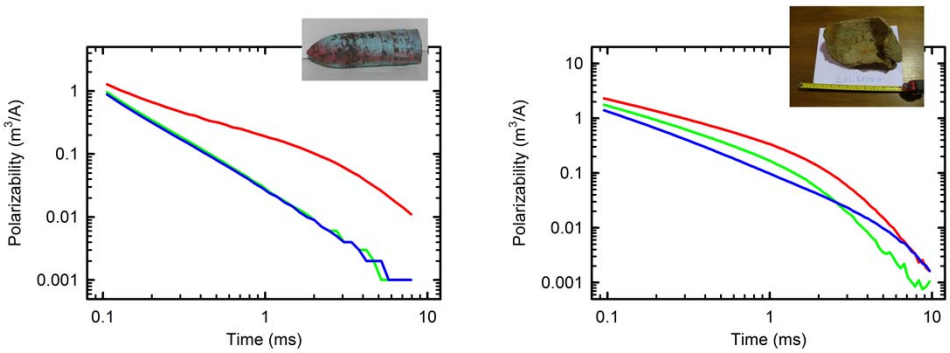
26 **Classification Basics** **RITS 2014: Using Classification Capable Sensors on MRP**



Target parameters are estimated using an iterative process called geophysical inversion. An initial guess is made for these parameters, the signal that would result is calculated, and this calculated signal is compared to the measured data. If they do not match the parameters are adjusted slightly and the cycle repeats. After thousands of cycles (easy for a computer) we achieve a good match between the calculated and measured signals and we can be confident we have the target parameters.

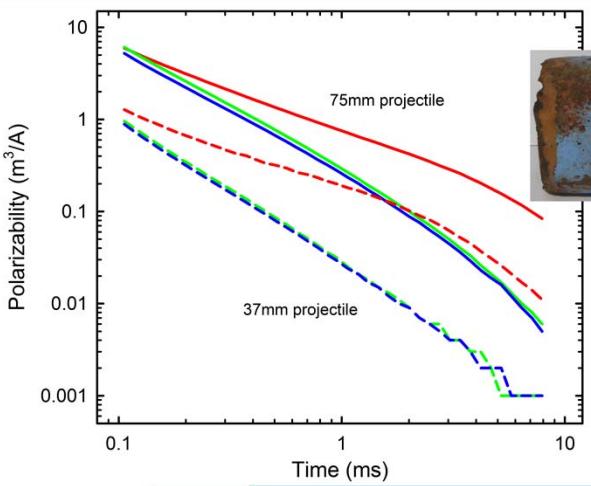
Polarizabilities → Classification

Intrinsic responses (polarizabilities) along target's principal axis directions fully characterize EMI signal



All Target Photo Insets Courtesy ESTCP

Size Comparison



Key Point Amplitude scales with object volume

Stages in the Classification Process

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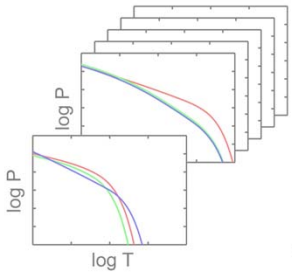

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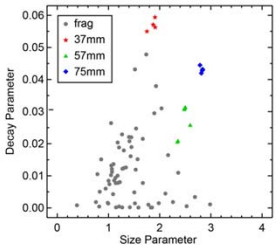

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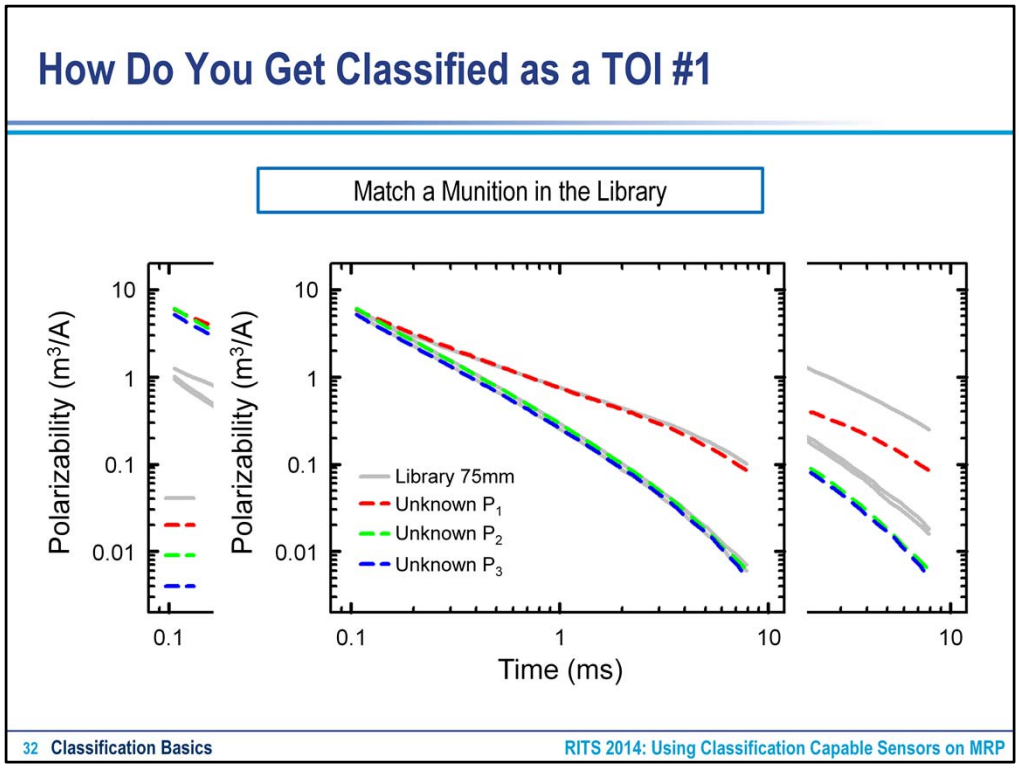
Classification Result

- "Can't Analyze" – must be dug
- Targets of Interest (TOI) – must be dug
- Everything Else – can be left in the ground


How Do You Get Classified as a TOI #1
Match a Munition in the Library
Polarizability (m³/A)
10
1
0.1
0.01
0.1
1
10
Time (ms)
Library 75mm
Unknown P1
Unknown P2
Unknown P3
32 Classification Basics
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You Don't Have To Be Whole to Match The Library

Classified as TOI, Type = 155

Classified as TOI, Type = 155

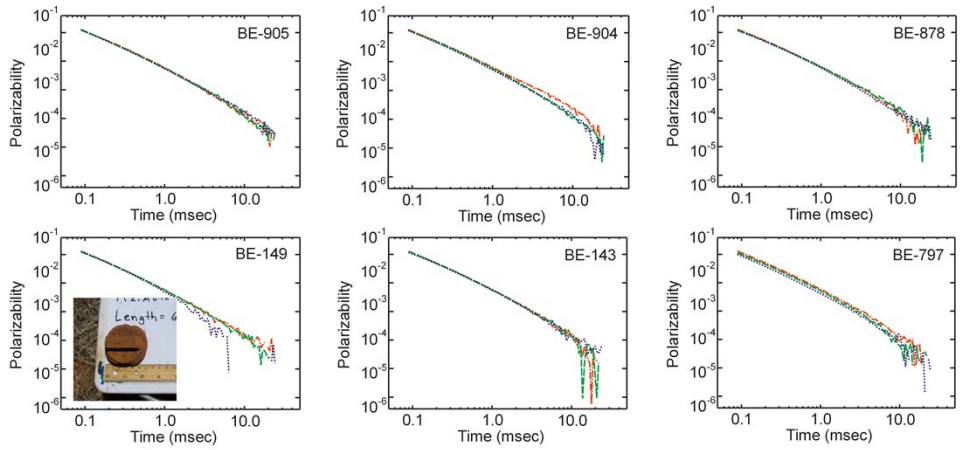
Classified as TOI, Type = 155

Classified as TOI, Type = 105

33 Classification Basics RITS 2014: Using Classification Capable Sensors on MRP

How Do You Get Classified as a TOI #2

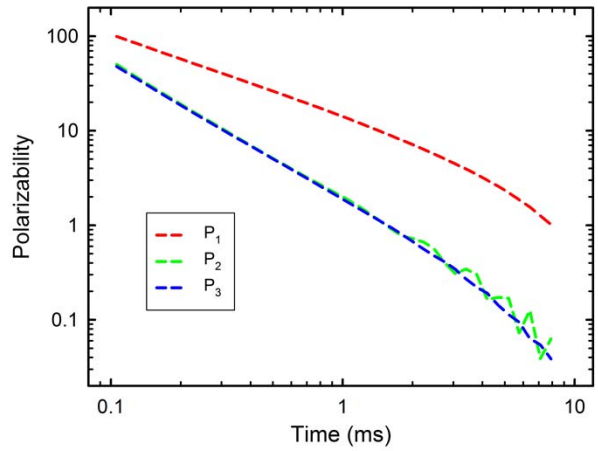
Be Part of a Cluster of Similar Items That Turn Out to Be TOI



6 of 25 in cluster

How Do You Get Classified as a TOI #3

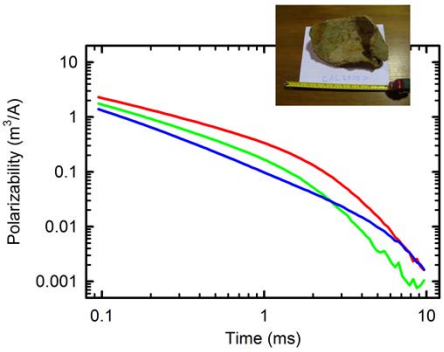
Be Big, Symmetric, and Thick-Walled



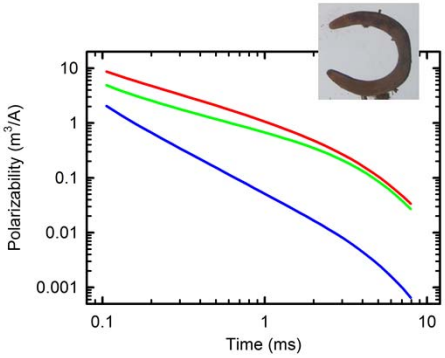
3-in stokes @ SLO

How You Get Classified as Clutter

No Symmetry



Known Clutter Item



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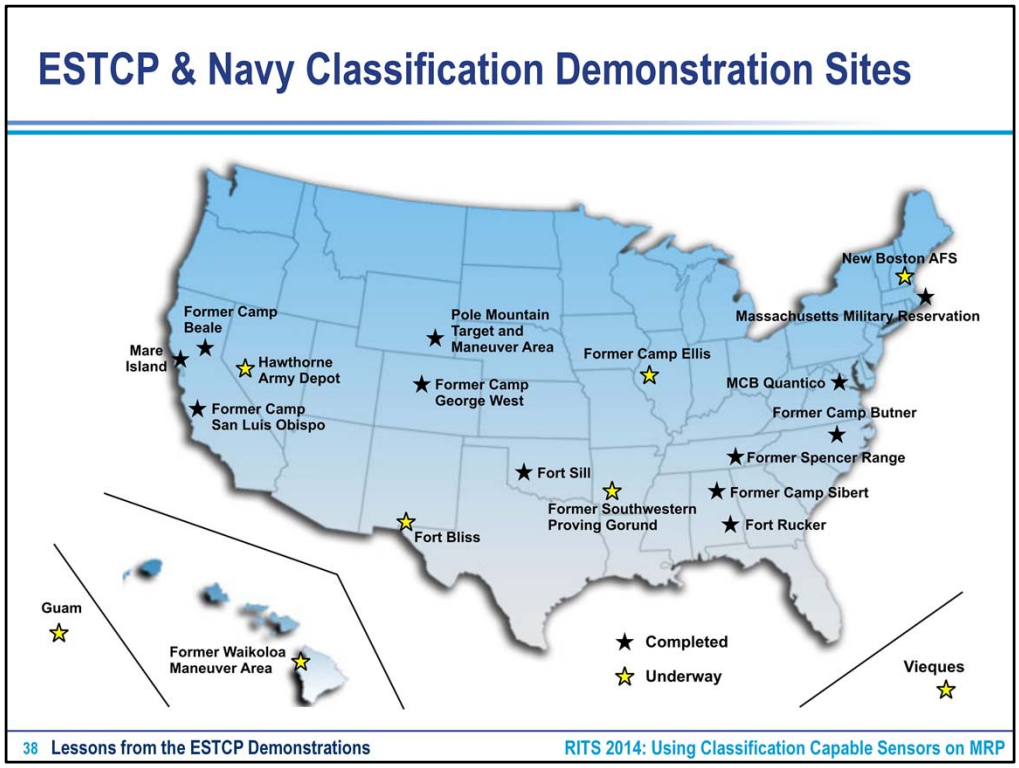
ESTCP & Navy Classification Demonstration Sites
New Boston AFS
Massachusetts Military Reservation
Former Camp Beale
Mare Island
Hawthorne Army Depot
Former Camp San Luis Obispo
Pole Mountain Target and Maneuver Area
Former Camp George West
Former Camp Ellis
MCB Quantico
Former Camp Butner
Former Spencer Range
Fort Sill
Former Southwestern Proving Gorund
Former Camp Sibert
Fort Rucker
Fort Bliss
Guam
Former Waikoloa Maneuver Area
Completed
Underway
Vieques
38 Lessons from the ESTCP Demonstrations
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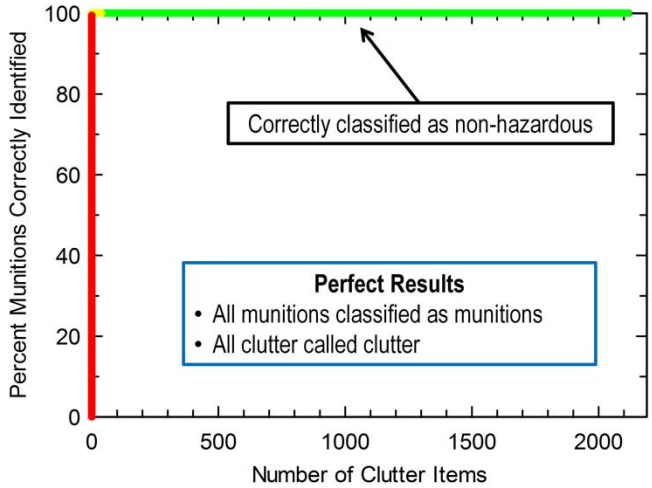
Performance Evaluation

Receiver Operating Characteristic (ROC) Curve

Rank	Comment
1	
2	High confidence munition
3	
…	Can't make a decision
…	Can't make a decision
…	
…	
…	High confidence clutter
…	
…	
…	
…	
N	



Performance Evaluation (cont.)

Receiver Operating Characteristic (ROC) Curve

Rank	Comment
1	
2	High confidence munition
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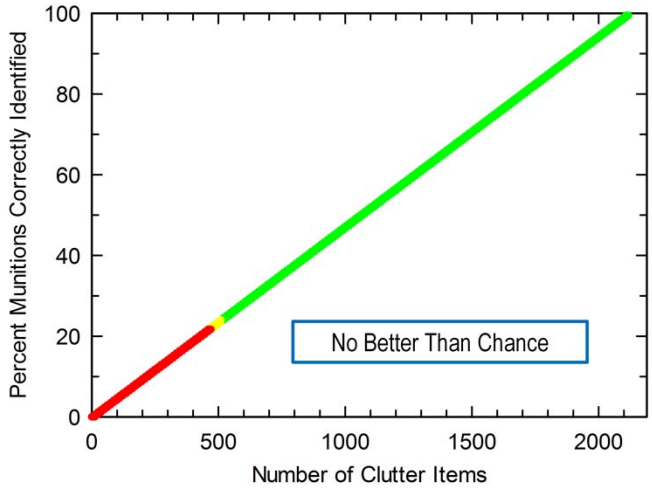
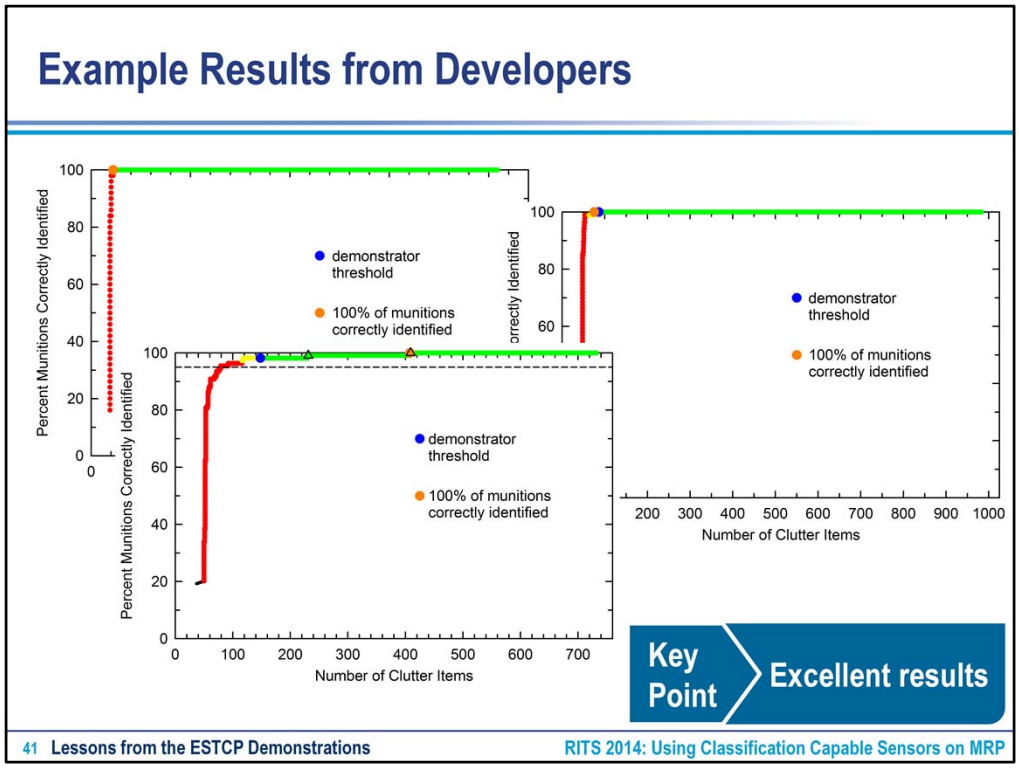
…	
…	
…	High confidence clutter
…	
…	
…	
…	
N	




Example Results from Developers
Percent Munitions Correctly Identified
demonstrator threshold
100% of munitions correctly identified
Number of Clutter Items
Key Point
Excellent results
41 Lessons from the ESTCP Demonstrations
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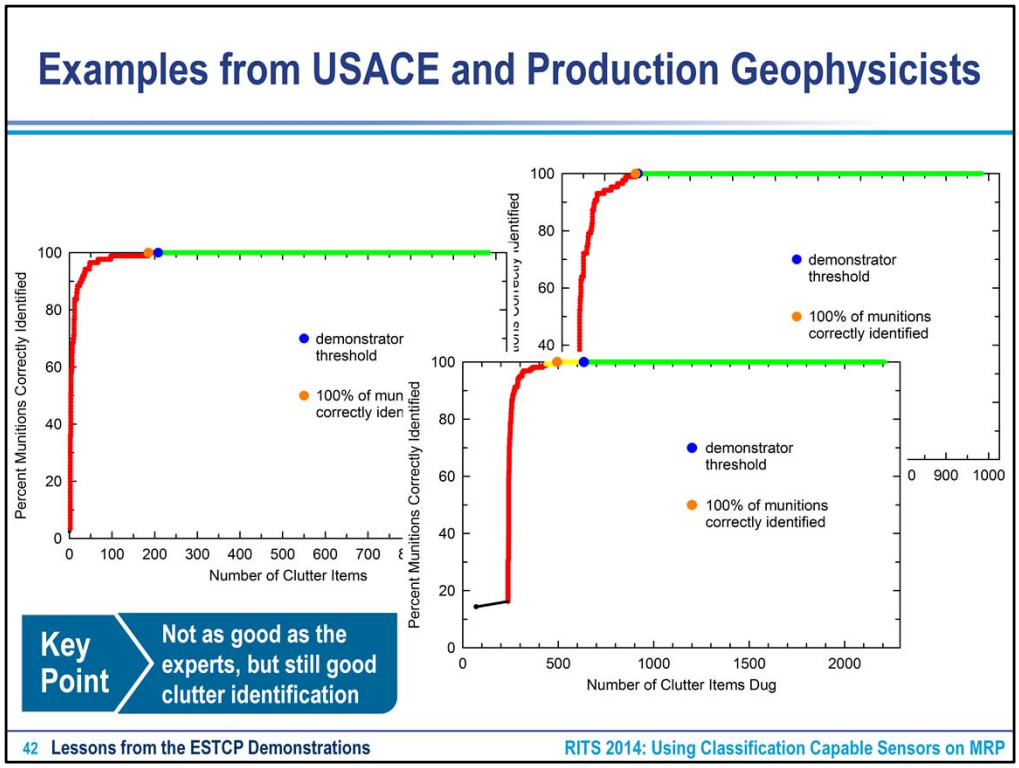
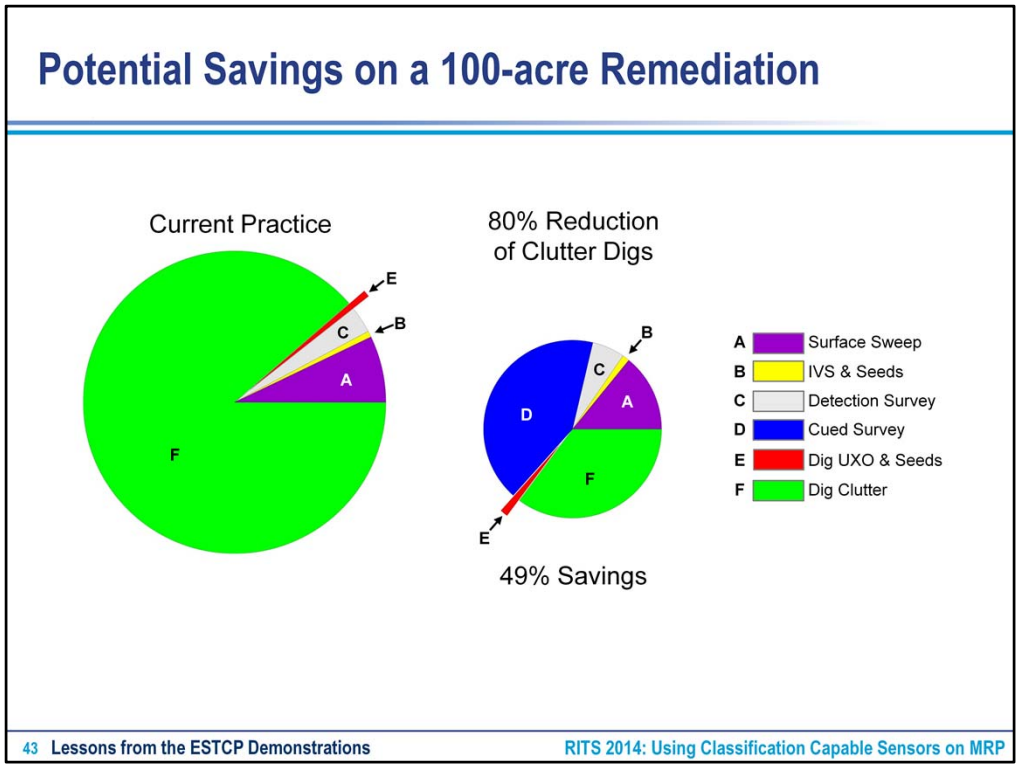

Examples from USACE and Production Geophysicists
Percent Munitions Correctly Identified
Number of Clutter Items
demonstrator threshold
100% of mun correctly iden
Percent Munitions Correctly Identified
Number of Clutter Items Dug
demonstrator threshold
100% of munitions correctly identified
demonstrator threshold
100% of munitions correctly identified
Key Point
Not as good as the experts, but still good clutter identification
42 Lessons from the ESTCP Demonstrations
RITS 2014: Using Classification Capable Sensors on MRP


Potential Savings on a 100-acre Remediation
Current Practice
80% Reduction of Clutter Digs
49% Savings
A Surface Sweep
B IVS & Seeds
C Detection Survey
D Cued Survey
E Dig UXO & Seeds
F Dig Clutter
43 Lessons from the ESTCP Demonstrations
RITS 2014: Using Classification Capable Sensors on MRP

Not Only Direct Cost Savings

- Fewer holes ⟶ less environmental damage
  - Wetlands
  - Sensitive environments
  - Golf courses
- Fewer digs ⟶ less disruption and fewer evacuations
- More sustainable practice

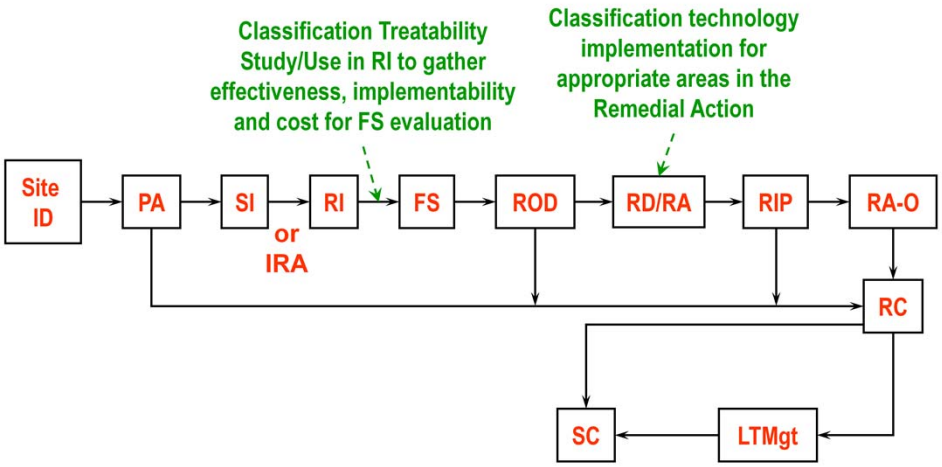
Regulator & Stakeholder Buy-In

- ESTCP Advisory Group
  - Service Representatives
  - US EPA
  - State Regulators
- Interstate Technology & Regulatory Council (ITRC) Team
  - Geophysical Classification for Munitions Response
- Implementation Recommendations
  - QC/QA procedures
  - Analyst qualifications

Classification Using Advanced Sensors

- Methods proven at nearly 20 demonstrations
- Can be successfully implemented by Government and production geophysicists
  - All TOI correctly classified
  - 80% reduction in clutter digs possible at many sites
- Big cost savings possible
- Not for every site
  - Very small sites with few anomalies
  - Most anomalies are TOI
  - Disposal sites and dumps

Navy Munitions Response
Cleanup Process with Classification Technology



Presentation Overview

- Classification Overview
- Classification Basics
- Lessons from the ESTCP Demonstrations
- Update on Sensors, Deployment, and Data Analysis
- QC/QA Considerations
- Example Project
- Wrap Up

Sensors and Deployment

- **Wide variety of deployment conditions**
- **Detection survey using advanced sensors**
  - **Mostly used a two-step approach until now**
    - Traditional detection survey (often EM61-MK2)
    - Static data collection over each anomaly using advanced sensor
- **Higher anomaly densities**
- **Updates to sensor underway**

Diversity of Deployment Platforms: MetalMapper

Courtesy ARCADIS (Top Left)

Courtesy Parsons (Top Right, Middle Right, Bottom Right, Bottom Left

Diversity of Deployment Platforms: TEMTADS 2x2

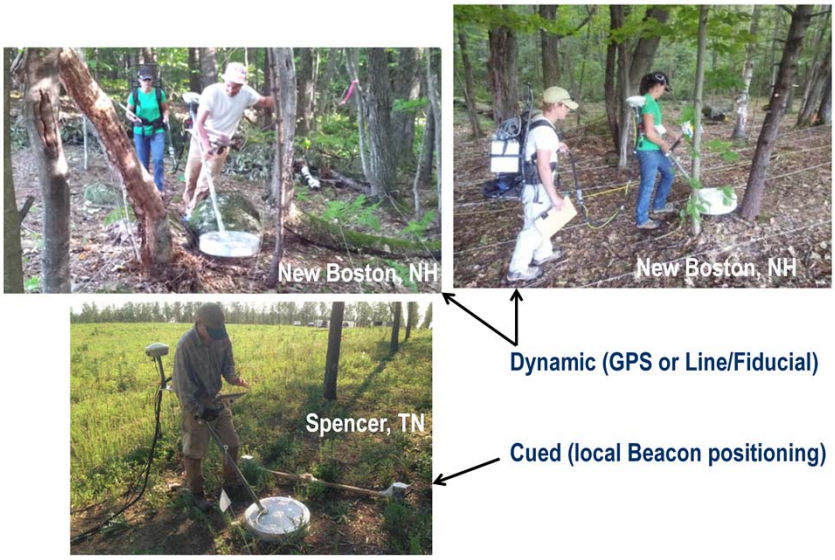
Courtesy URS

Courtesy CH2M Hill

Courtesy NOVA Research

Courtesy URS

Diversity of Deployment Platforms: MPV



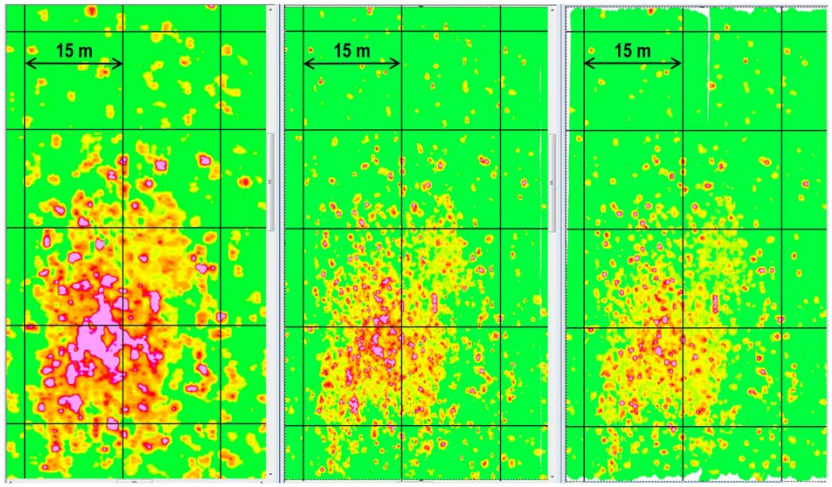
Dynamic (GPS or Line/Fiducial)

Cued (local Beacon positioning)

Photos Courtesy Sky Research

Comparison of Survey Data

Camp Ellis



EM61 MetalMapper TEMTADS 2x2

Comparison of Survey Data (cont.)

Seed Offsets

Spencer Dynamic Area Data

	Avg.	Max	% > 40 cm
EM61	27 cm	54 cm	17%
TEMTADS 2x2	12 cm	28 cm	0%

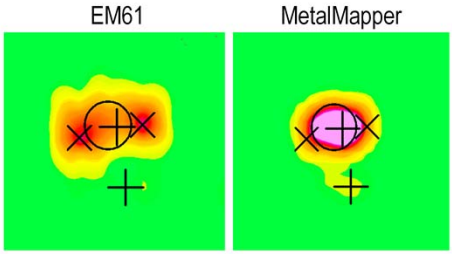
Ellis Dynamic Data

	Avg.	Max	% > 40 cm
EM61	33 cm	100 cm	29%
MM	18 cm	50 cm	4%

- **Rethink acceptable offset: standard (~60 – 80 cm) vs. Cued (40 cm)**
- **Time wasted searching with 'dancing arrows' & recollects**
- **Potentially collect wrong target**

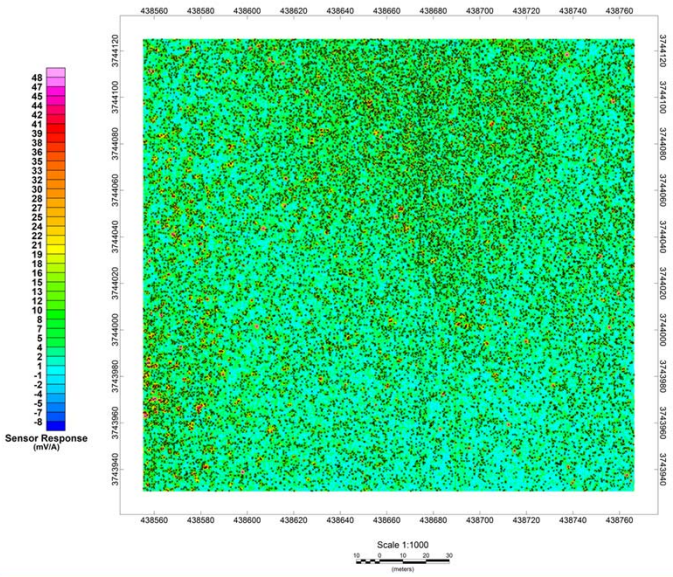
Comparison of Survey Data (cont.)

Seed Offsets



○ 2.36" rocket
X EM61- 0.74m offset
+ MM- 0.2m offset

Higher Anomaly Densities



Southwestern Proving Ground

20 mm projectiles

>2,000 anomalies/acre

Higher Anomaly Densities (cont.)

Courtesy CH2M Hill

New Boston AFS

20 mm projectiles

>3,000 anomalies/acre

Lessons From Demonstrations

- Experience matters in both data collection and data analysis
  - This is harder than picking peaks from EM61 data
  - Many production geophysicists continue to perform well
  - We all need to keep our eyes on training
- Initial results point toward success with 20 mm projectiles
  - Very expensive
  - Only put these items on the TOI list if you really mean it
- Communication is the key to making this work
  - Good characterization data communicated to the analysts
  - Good communication with the intrusive crew

Updates to Advanced Sensors

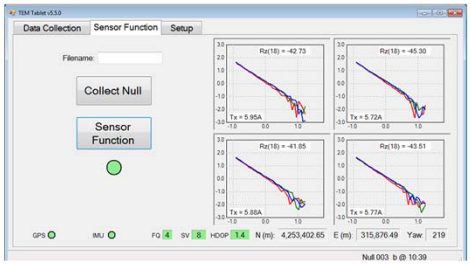
- Sensors being ruggedized for routine field use
- Implementing in-field data QC
- MetalMapper Improvement Project from Geometrics

Updates to Data Acquisition Software

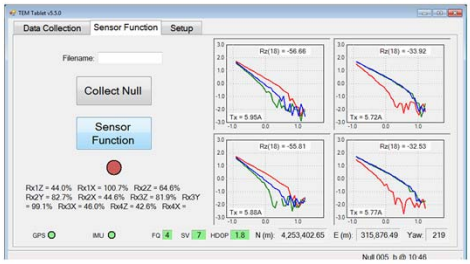
- **TEMTADS 2x2**
  - **Sensor function test**

Courtesy NOVA Research

pass

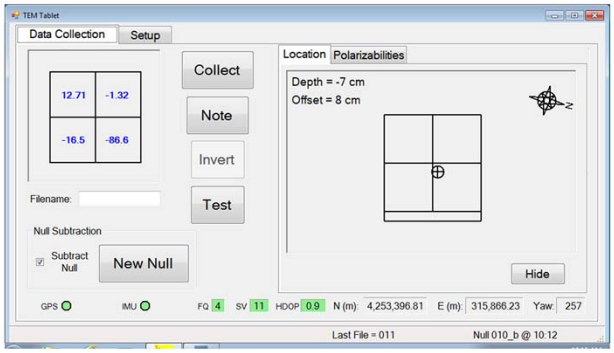


fail



Updates to Data Acquisition Software (cont.)

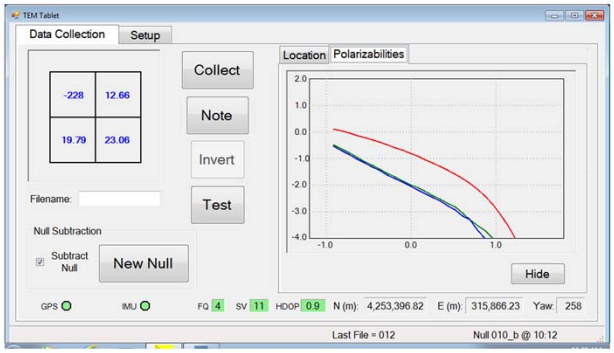
- **TEMTADS 2x2**
  - **In-field inversion**



Invert – Check Offset

Updates to Data Acquisition Software (cont.)

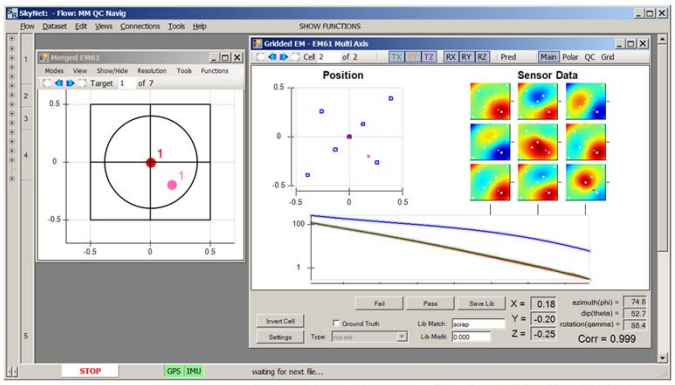
- **TEMTADS 2x2**
  - **In-field inversion**



Invert – View Polarizabilities

Updates to Data Acquisition Software (cont.)

- **MetalMapper**
  - **Similar updates**



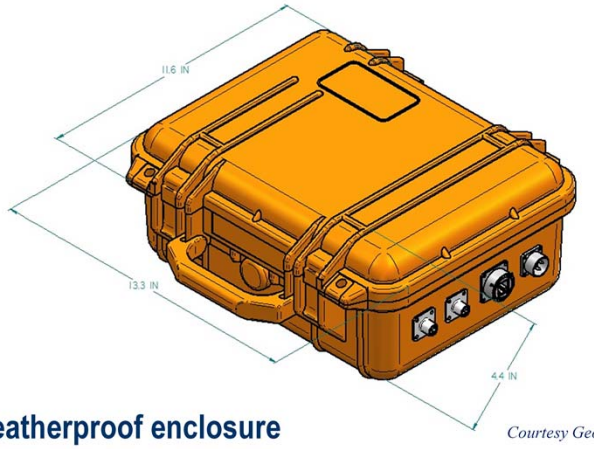
Courtesy White River Technologies

- **Inverted position check**
- **'Green light' GPS/IMU**
- **Polarizability plot & library match**

Update from Geometrics

- ESTCP Project to ruggedize & standardize MetalMapper
  - Hardware improvements
  - Software simpler and more robust
- New version expected for sale/rent in Fall/Winter 2014

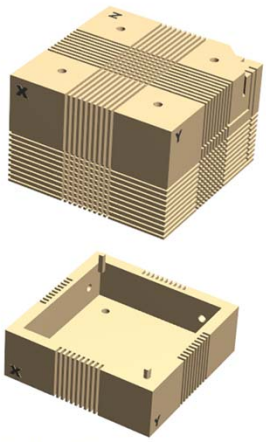
Ruggedized Electronics Packaging



Courtesy Geometrics

- **Weatherproof enclosure**
- **Reduced number of connectors**

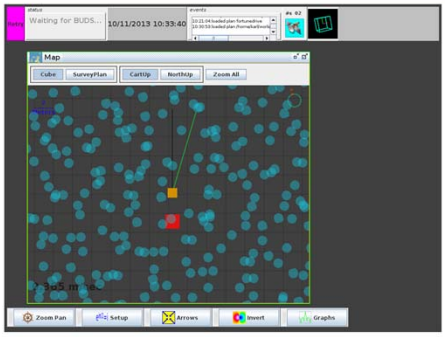
Ruggedized Construction of Tx and Rx

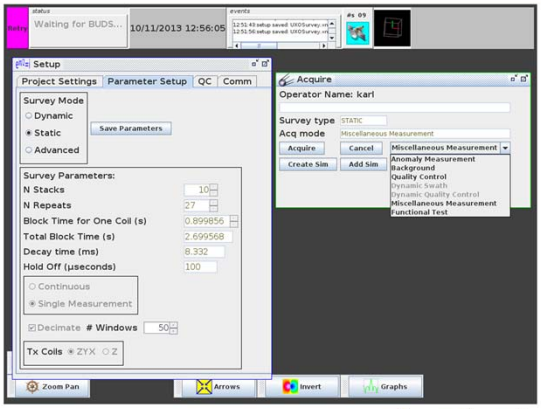


Courtesy Geometrics

- **3D printing techniques used for receiver cubes**
  - **Less sensitive to effects of moisture**
  - **No change to response**
- **Currently evaluating costs for 3D printed transmitter coils**
  - **Too large to print as single item**
  - **Current Goal: 3D print complex parts (*i.e.*, corners) and used milled plastic stock for sides**
    - This will allow simpler design/construction of multiple transmitter coil sizes
- **Development of 3D models will allow easy transition to molded parts for increased production at lower cost**

Simplified Software Interface





Courtesy Geometrics

- Increased use of icons to display QC information
- Integrated in-field inversions
- Increased QC checks
- Automated reminders for background measurements
- Simplified parameter input
- Data stored in open source format

- completely rewriting interface
- extra setup options no one needed to change- used to confuse
- Many QC tools similar to TT & SkyNet
- Moving from proprietary data interface to open-source – more normal field instrument

Availability of Advanced Sensors

- ~10 MetalMappers
  - 4 USACE – GFE
  - Rent $500/day
  - Late Fall/Winter – New model at substantial cost reduction
- ~6 TEMTADS 2x2
  - NAVFAC at Vieques
  - NRL – GFE
  - Within year – Available for purchase from Geometrics
- 1 MPV
  - Possible transition – Updated electronics package will be usable

Sensors

- Advanced sensors can be used anywhere DGM is appropriate
- Sensors are starting to become routinely available
- Implementation improvements in the next generation will widen their use

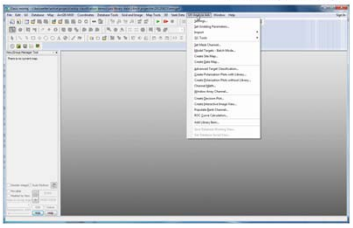
Analysis Software

- Major improvements to workflow in UX-Analyze
  - Reduce routine load on the analyst
  - Focus analyst time on QC issues
  - Standardize data views and outputs
- Released first to "power users" for comment
  - General release in February 2014
- Training started in April

Software Overview

- UX-Analyze is fully integrated into Oasis montaj as a menu-driven set of functions for geophysical target characterization and classification
- These functions permit users to effectively classify munitions targets
- Released to the US Government and commercial contractors
  (free of charge to recipients)

Courtesy Geosoft



Processing Flow

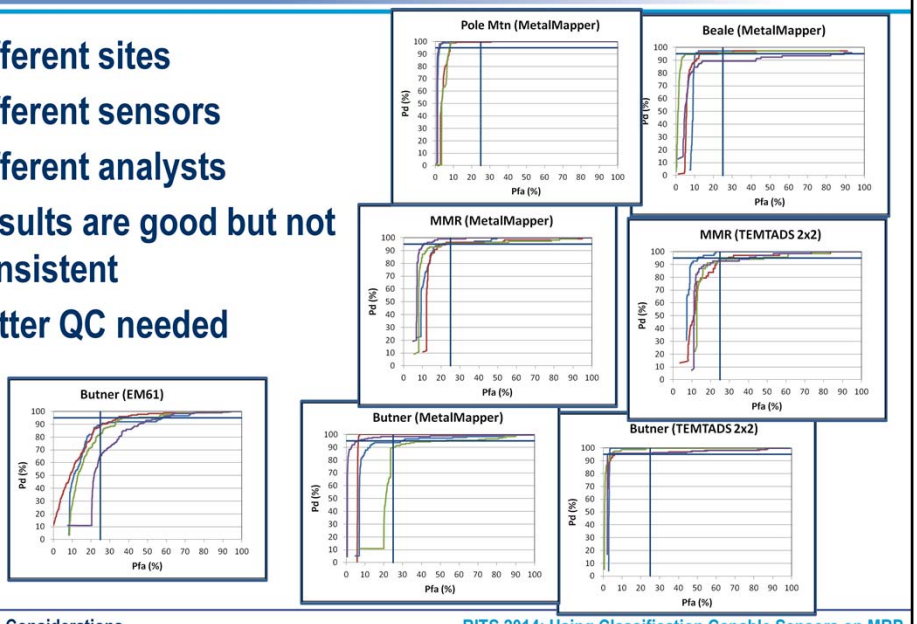
- **Fundamental Analysis Steps**
  1. Construct a Library (Expected Munitions and Clutter)
  2. QC Measured Data (Blind and Background)
  3. Invert and Look for Expected Munitions
  4. Look for Unexpected Munitions
  5. Prioritize
- **Results and final products**

Presentation Overview

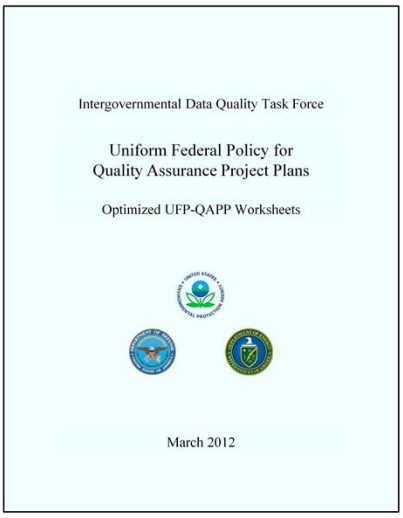
- Classification Overview
- Classification Basics
- Lessons from the ESTCP Demonstrations
- Update on Sensors, Deployment, and Data Analysis
- QC/QA Considerations
  - Draft QAPP for Classification Applied to Munitions Response
  - Examples of QC Tests Being Developed
    - Sensor Function
    - Data Integrity
    - Background Removal
    - QC Seeds to Manage Expectations
    - Stop Dig Point
- Example Project
- Wrap Up

Recent Demonstration Results Demonstrate Need for Better QC

- Different sites
- Different sensors
- Different analysts
- Results are good but not consistent
- Better QC needed



UFP-QAPP for Classification


Intergovernmental Data Quality Task Force

Uniform Federal Policy for
Quality Assurance Project Plans

Optimized UFP-QAPP Worksheets

March 2012

- ESTCP & CA DTSC developed a draft Quality Assurance Project Plan for Classification Applied to MR
- Handed off to a workgroup of the Intergovernmental Data Quality Task Force
- Field test this summer at San Luis Obispo in conjunction with USACE

Worksheets Included

1 & 2	Title and Approval Page	**13**	Secondary Data Uses and Limitations
3 & 5	Project Organization and QAPP Distribution	**14 & 16**	Project Tasks and Schedule
4, 7, & 8	Personnel Qualifications and Sign-off Sheet	**17**	Sampling Design and Project Work Flow
6	Communication Pathways	**20**	Quality Control and Corrective Action
9	Project Planning Session Summary	**21**	Field and Data Analysis SOPs
10	Conceptual Site Model	**29**	Project Documents and Records
11	Data Quality Objectives	**34**	Final Data Verification
12	Measurement Performance Criteria		

SOPs Included

⊗	1	Assemble the MetalMapper System and Verify Correct Operation
⊗	2	Test Sensor and System at the IVS
⊗	3	Production Area Seeding
◆	4	Collect Dynamic Data Using the MetalMapper Sensor
★	5	Preprocess Dynamic Data and Identify Anomalies
◆	6	Collect Static Background Measurements
◆	7	Collect Cued Target Measurements
★	8	Verify Usability of Advanced Sensor Data
★	9	Background Correct Cued Anomaly Data
★	10	Invert Anomaly Data to Extract Source Parameters
⬡	11	Compare Extracted Parameters to MEC Signatures in the Data Library
⬡	12	Develop Prioritized Dig List using Library Matching and Other Factors
⊕	13	Verify Recovered Objects are Compatible with Predictions based on the Advanced Sensor Data
⊕	14	Develop Verification Sampling Dig List and Perform Verification Sampling

⊗ Pre-Survey
◆ Geophysical Data
★ Extract Parameters
⬡ Classify
⊕ QA

Example QC and QA Recommendations

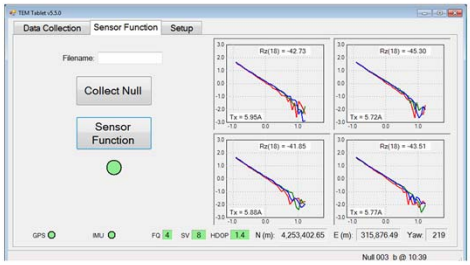
- QC
  - Sensor Function QC
  - Data Integrity QC
  - Background Removal QC
- QA
  - QC Seeds can guide threshold determination
  - Was the stop-dig point chosen correctly?

Sensor Function QC

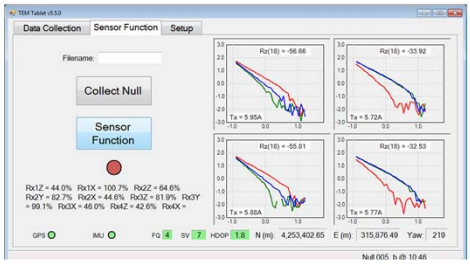
- **TEMTADS 2x2**
  - **Sensor function test**

Courtesy NOVA Research

pass

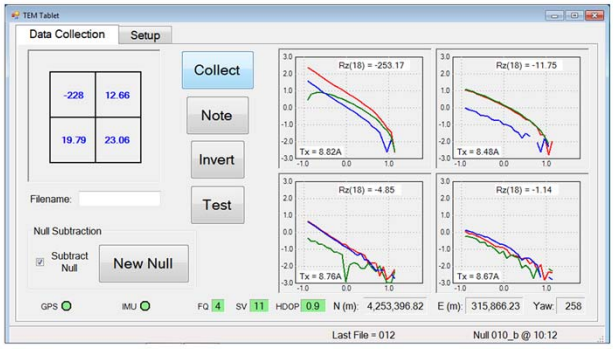


fail



Data Integrity QC

- **TEMTADS 2x2**
  - **Collect quality data**

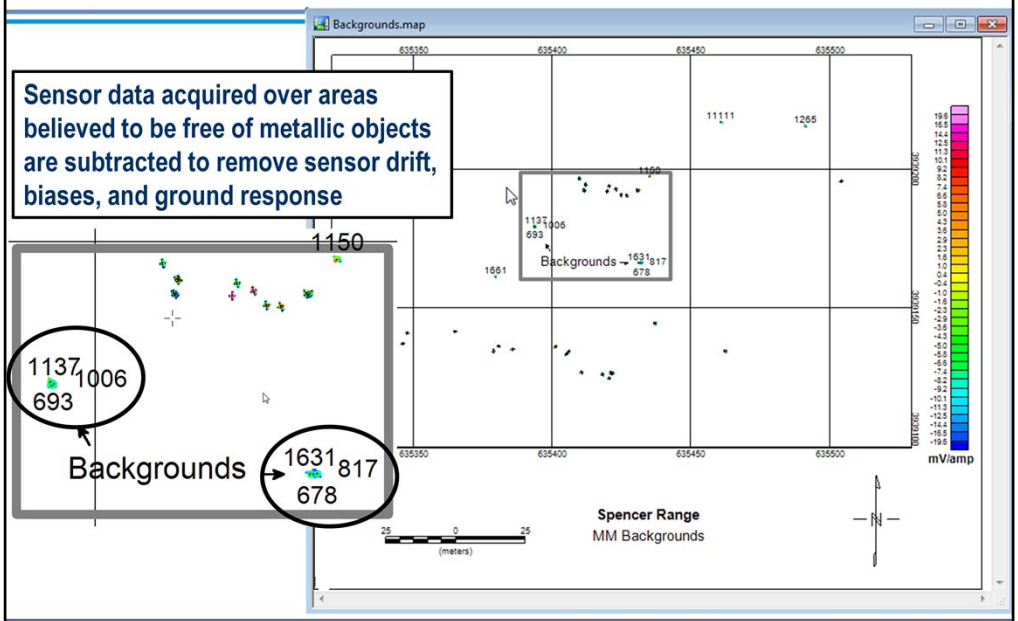


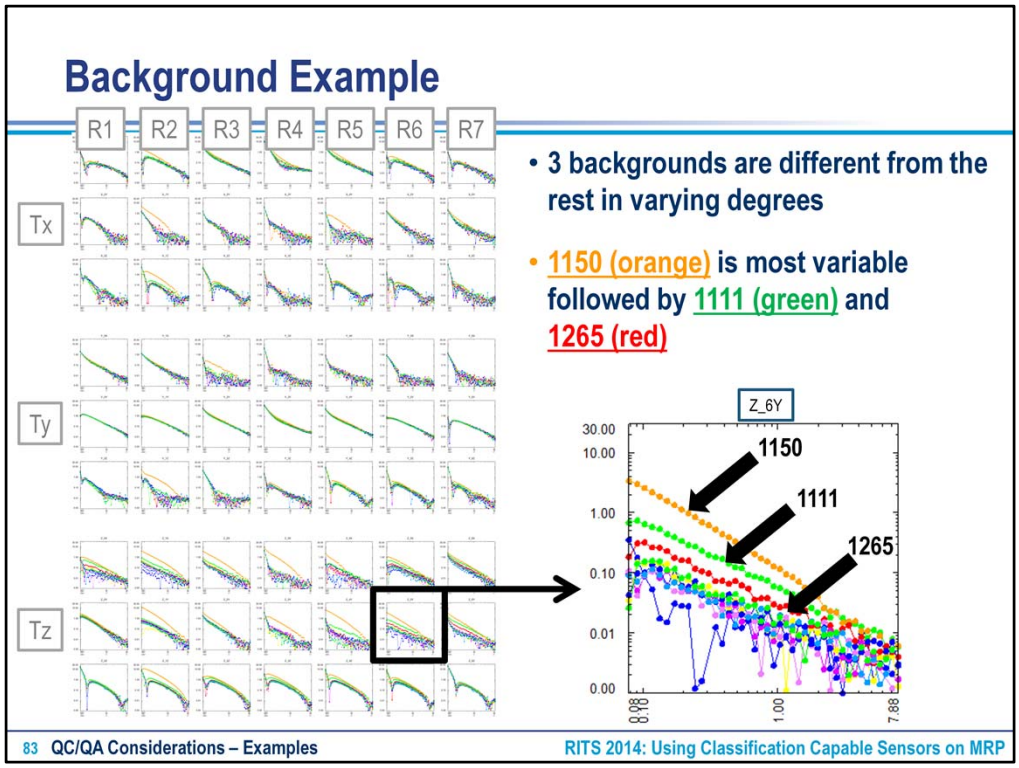
Collect Data – Check GPS/IMU Quality

Background Removal QC

- Background corrections applied to remove:
  1. Soil response
  2. 'Zero level' drift
- Therefore background measurements must:
  1. Be taken in similar soils to that of the target (minimize the spatial offset)
  2. Be taken frequently (minimize temporal offset)
  3. Be free of signal due to metal sources

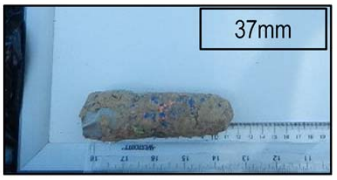
QC Static Backgrounds



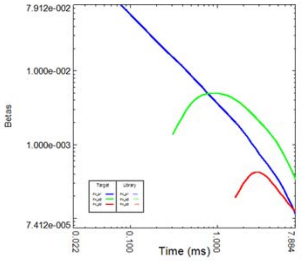

Background Example
R1
R2
R3
R4
R5
R6
R7
Tx
Ty
Tz
• 3 backgrounds are different from the rest in varying degrees
• 1150 (orange) is most variable followed by 1111 (green) and 1265 (red)
Z_6Y
30.00
10.00
1.00
0.10
0.01
0.00
1150
1111
1265
0.18
1.00
7.88
83 QC/QA Considerations – Examples
RITS 2014: Using Classification Capable Sensors on MRP

Low Amplitude Signatures are Preferentially Affected by Questionable Backgrounds

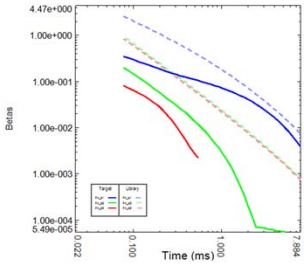
Result of subtracting the three different backgrounds shown earlier on a seeded 37mm…



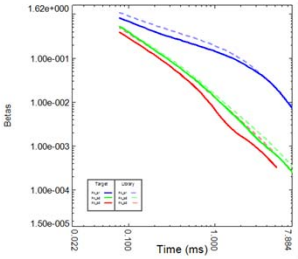
Match Metric
1150 as background
No Match



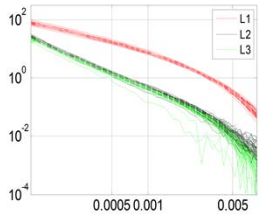
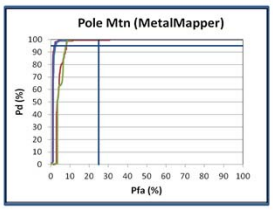
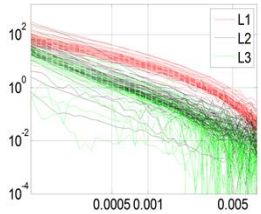
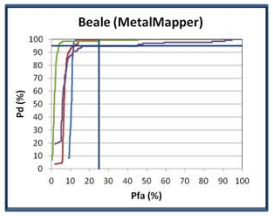
Match Metric
1111 as background
37mm; 0.35 metric



Match Metric
1265 as background
37mm; 0.86 metric



QC Seeds as a Measure of Local Geology

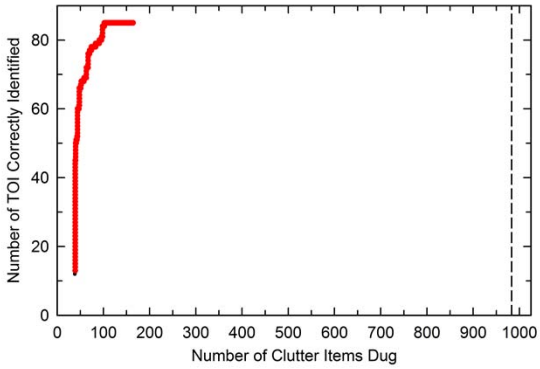
Local Geology	Feature Extraction (small ISO)	Classification Results
Pole Mtn. (resistive)		
Beale (conductive)		

Is the Stop Dig Point Correct?

Final Ranked Anomaly List

Anomaly ID	Dig	Type	Comment
2498	1		Training Data
247	1		
1114	1		Can't extract reliable parameters
69	1	105	
811	1	48	High likelihood TOI
313	1	37	
883	0		
1642	0		High likelihood not TOI
713	0		
406	0		
…	0		
…	0		
…	0		
…	0		
…	0		
…	0		

Stop Dig Threshold



In real life we only know the part we dig (including TOI)!

Stop Dig Point

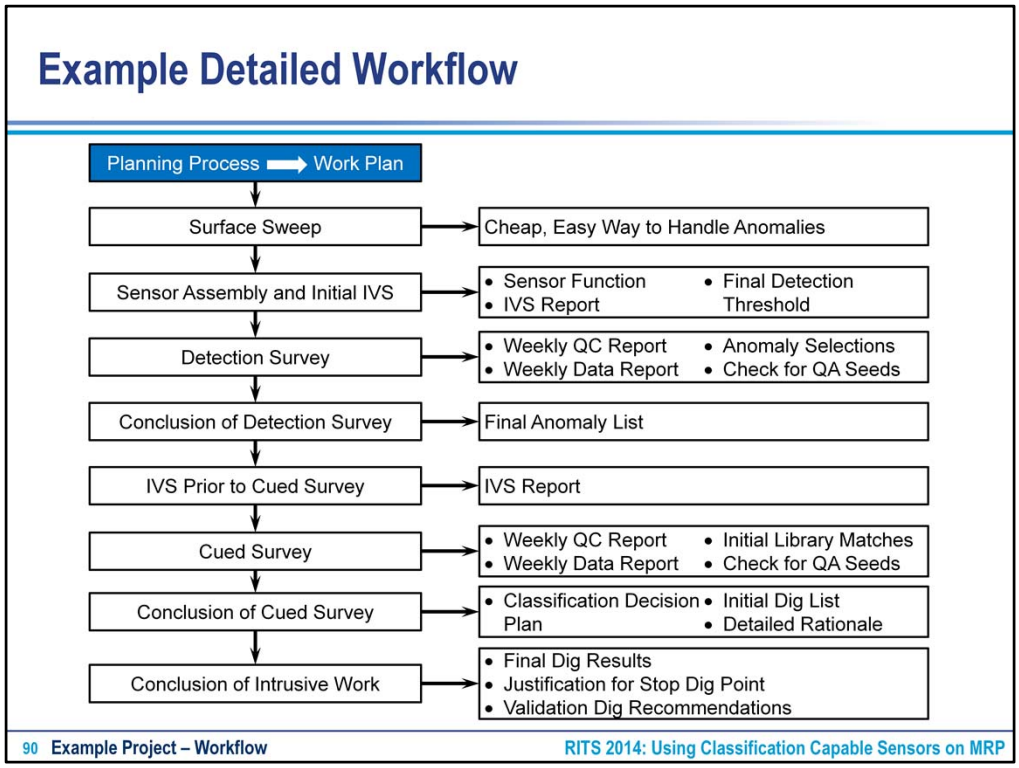
- **QC Results**
  - **All seeds were detected**
  - **All seeds were correctly classified**
  - **All excavated items matched the prediction**
- **What more can we do?**
  - **Verify every decision threshold**
  - **Randomly check the clutter**
    - Little to no chance of finding UXO
    - Make sure excavated item matches predictions

Presentation Overview

- Classification Overview
- Update on Sensors and Deployment
- Update on Data Analysis
- QC/QA Considerations
- Example Project
- Wrap Up

Project Planning: Questions To Ask Yourself

- What targets am I interested in classifying? What is the anomaly density?
- What sensor is appropriate for my terrain and vegetation?
- Do I need to remove 100% of the hazard? The bulk of the hazard? Or just characterize the site?
- Do I need to consider a dynamic survey with an advanced sensor?
- Will I end up digging the majority of the detections?
- Are there qualified and experienced people available?


Example Detailed Workflow
Planning Process → Work Plan
Surface Sweep
Cheap, Easy Way to Handle Anomalies
Sensor Assembly and Initial IVS
• Sensor Function
• IVS Report
• Final Detection Threshold
Detection Survey
• Weekly QC Report
• Weekly Data Report
• Anomaly Selections
• Check for QA Seeds
Conclusion of Detection Survey
Final Anomaly List
IVS Prior to Cued Survey
IVS Report
Cued Survey
• Weekly QC Report
• Weekly Data Report
• Initial Library Matches
• Check for QA Seeds
Conclusion of Cued Survey
• Classification Decision Plan
• Initial Dig List
• Detailed Rationale
Conclusion of Intrusive Work
• Final Dig Results
• Justification for Stop Dig Point
• Validation Dig Recommendations
90 Example Project – Workflow
RITS 2014: Using Classification Capable Sensors on MRP

Final Stage of Project

- Government prepares final validation plan
  - Test each decision threshold
  - Random digs of non-TOI to test inversion results
- Validation digs
- If no surprises, project is complete

Presentation Overview

- Classification Overview
- Update on Sensors and Deployment
- Update on Data Analysis
- Project Workflow and QC/QA
- Wrap Up

Final Thoughts

- Classification has been shown to provide significant efficiencies in risk reduction at Munitions Response sites
- Careful Planning and Quality Management are critical to reproducing this success at your site
  - UFP-QAPP
  - Rigorous QC program
  - Careful QA
- Continuous communication with all stakeholders

Application to Munitions Underwater

- Active topic in SERDP (R&D Program)
- Several aspects on the underwater environment make this tougher
  - Geolocation
  - Bottom stand-off
  - Ability of platform to "hover" over the object to be classified
- May have better luck with acoustic sensors