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A Method to Fuse Multi-Physics Waveforms and Improve Predictive Explosion Detection: Theory, Experiment, and Performance

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T3.5-Data Analysis Algorithms, #127

POSTER

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ABSTRACT

Abstract and CTBTO Relevance

Quantitative methods that enable multi-physics waveform fusion support explosion monitoring and general research in geophysical processes that comprises background emissions for explosion monitoring. We offer a constructive method to fuse statistics that we derive from multi-physics waveforms and improve our capability to detect small, above-ground explosions over methods that consume single waveforms. Our method advances Fisher's Method to operate under both hypotheses of a binary test on noisy data and provides density functions required to forecast our ability to screen fused explosion signatures from noise. We apply this method against 12-day, multi-signature chemical explosion and noise records to illustrate three primary results. We show that: (1) a fused multi-physics statistic that combines radio, acoustic, and seismic waveforms can identify explosions roughly 0.8 magnitude units lower than an acoustic emission, STA/LTA detector for the same detection probability; (2) we can quantitively predict how this fused, multi-physics statistic performs with Fisher's Method; and (3) that this data stream method competes well with lower fidelity, decentralized detection approaches. We additionally present our preliminary, but more general work that addresses multi-signature association of data streams to a common source.

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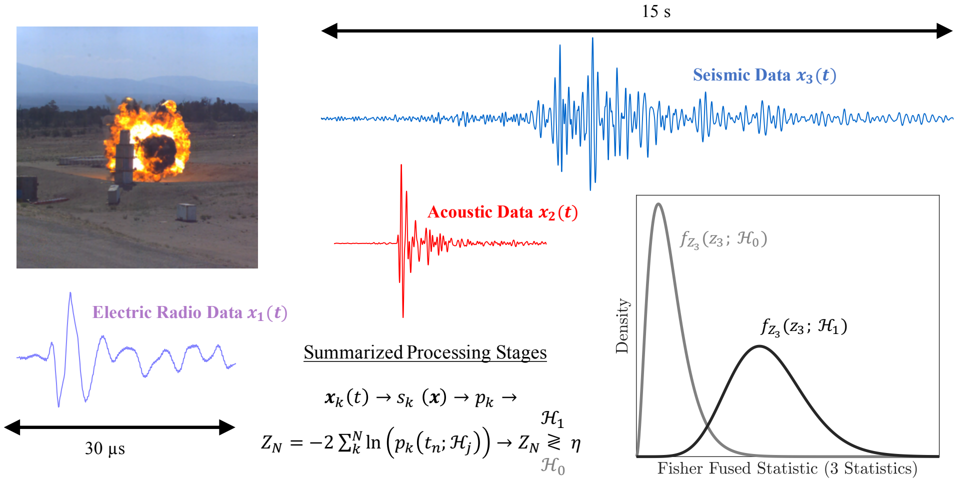
INTRODUCTION

Overview

Surface explosions near ground release electromagnetic and mechanical energy into their near-source environment, exciting radio, acoustic, and seismic signals that appear as waveforms in the radiation-dominated range of their sources (**right**). We fuse detection statistics output from single waveform detectors that process these data to deliver three main outcomes:

1. First, we build a method to fuse transformed *p*-values measured from multiple source signatures into a single data stream.
2. We match predicted and empirical performance curves to measure the probability and uncertainty that our method will detect explosion signatures against source size.
3. We apply our method against fused radio, acoustic, and seismic waveform detection statistics measured from near-ground, bare, solid charge explosions.

We show that the Fisher detector decreases detection thresholds, reduces false alarm rates, and improves our predictive capability to detect waveform signatures of near-ground explosions.



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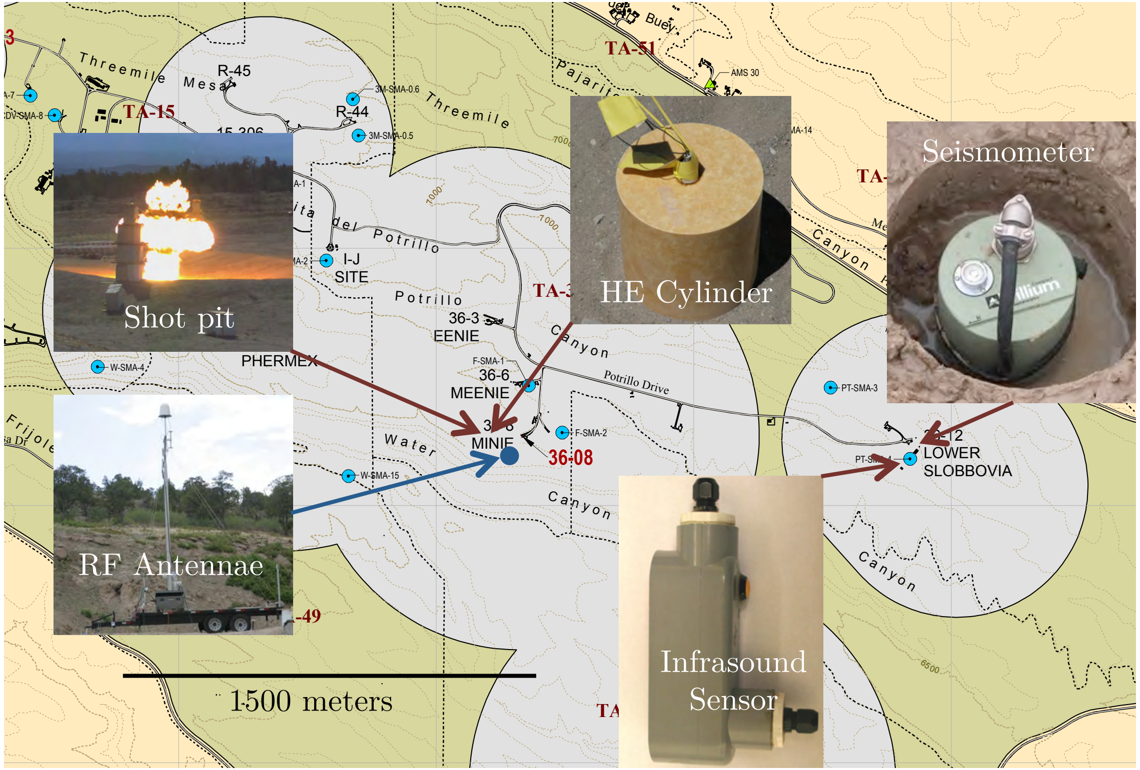
DATA SET

Tests

We performed parametric tests of 68 bare COMP-B charges detonated over 12 days at -1m to +4m heights of burst (HoBs) (above ground to below ground), in multiple noise environments

Mass	HoB (# Shots)	# Days
1.5kg	+4 (5), +1 (5)	4
5kg	+4 (4), +1 (6)	4
11kg	+4 (13), +2 (6), +1 (9), +0.5 (4), 0 (4), -1 (4)	10
15kg	+4 (7), +1 (3)	3



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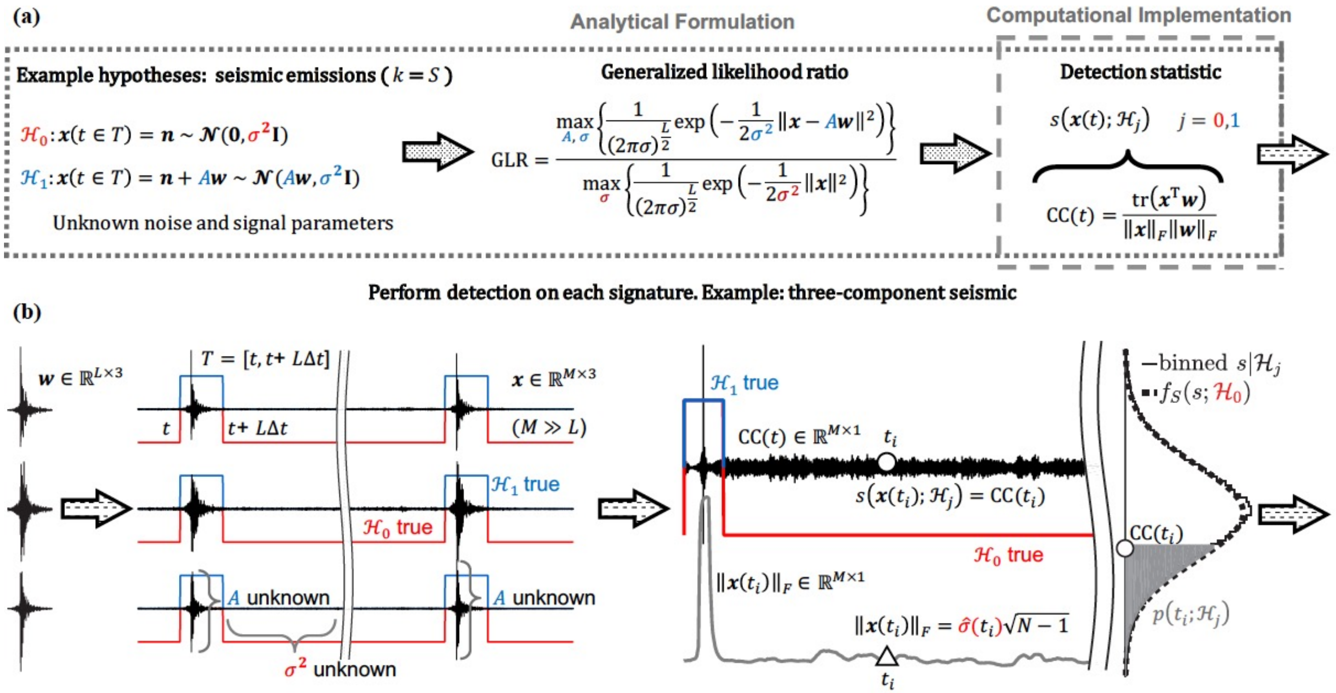
METHODS (1/3)

(**a**) We form detectors for any signature (seismic in this example) through a binary hypothesis test between two competing models of noisy data (left). The analytical ratio of PDFs (middle) defines a scalar detection statistic (right). In this case, the statistic is a correlation coefficient.

(**b**) A three channel seismic signal that records a near ground explosion defines a correlation detector template ***w*** (left). The detector scans this template against target data (middle) and where the CC value exceeds a threshold that is consistent with a false alarm rate, the data no longer are statistically consistent with the null hypothesis (right). The *p*-value does not have a chi-square distribution anymore. The conventional form of Fisher's test is now inapplicable.



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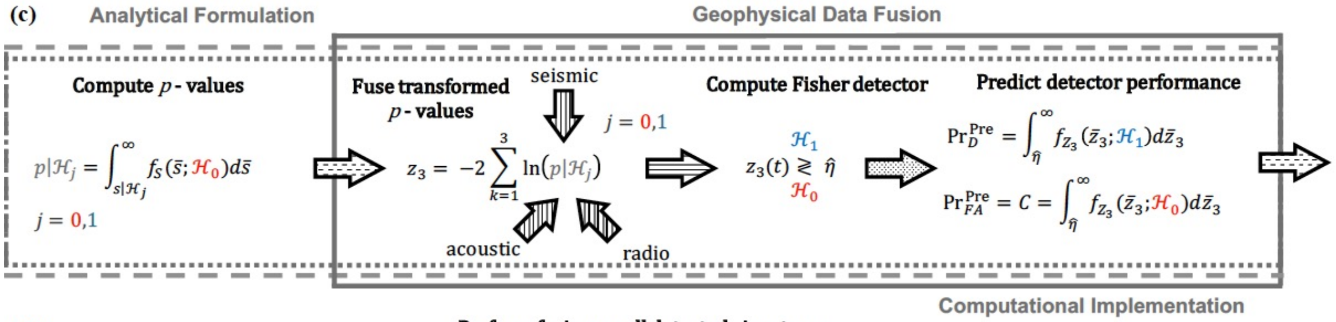
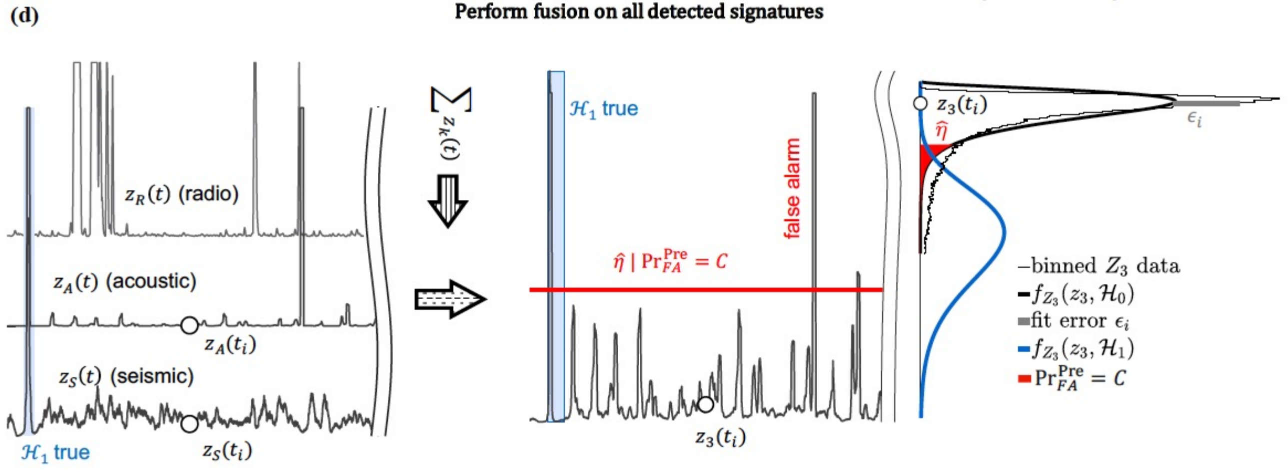
METHODS (2/3)

(**c**) We compute a p-value under each hypothesis (left) and fuse the multi-signature data that includes radio, acoustic, and seismic data using Fisher's combined probability test (middle). We set a threshold according to a false alarm rate. To **generalize** Fisher's test, we derive the **correct** PDF for the fused data assuming $\mathcal{H}_1$ when $z_3(t) > \eta$ (right).

(**d**) Data from our explosion data show single data streams (left), their fused data stream (middle), and their observed distributions (right). The curve overlap between the null and alternative hypothesis PDFs quantify the detection capability of the fused detector that produces the middle time series . This disagreement between the theoretical PDFs and normalized histogram define the error in the model.





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METHODS (3/3)

Predictive Detection Curves and Observed Detection Curves

Scale template waveforms of amplitude A_0 that record a reference source of magnitude m_0 to amplitude A, to mimic signals of source of magnitude $m = m_0 + \Delta m$ so: $A = 10^{\Delta m} A_0$. Then repeat and infuse this scaled waveform into noisy target data.

Constructing Predicted Performance Curves

- Construct PDF curves and compute detection rates at each $\Delta\boldsymbol{m}$ value, for many time windows
- Integrate the PDF over its concurrent detection threshold η to estimate detection probability $\mathrm{Pr}_D^{(\mathrm{Pre})}(\Delta\boldsymbol{m})$
- Scale probability by the true number of infused waveforms to estimate the expected number of counts $N \cdot \mathrm{Pr}_D^{(\mathrm{Pre})}(\Delta\boldsymbol{m})$

Constructing Observed Performance Curves

- Infuse scaled waveforms into real, recorded noise sampled from multiple times and over 12 days
- Process noisy waveforms with detectors over days and $\Delta\boldsymbol{m}$. Algorithms adjust detector thresholds η to maintain a fixed false alarm rate.
- Compare error-weighted, time-averaged detection counts that approximate $N \cdot \mathrm{Pr}_D^{(\mathrm{Obs})}(\Delta\boldsymbol{m})$ against $N \cdot \mathrm{Pr}_D^{(\mathrm{Pre})}(\Delta\boldsymbol{m})$

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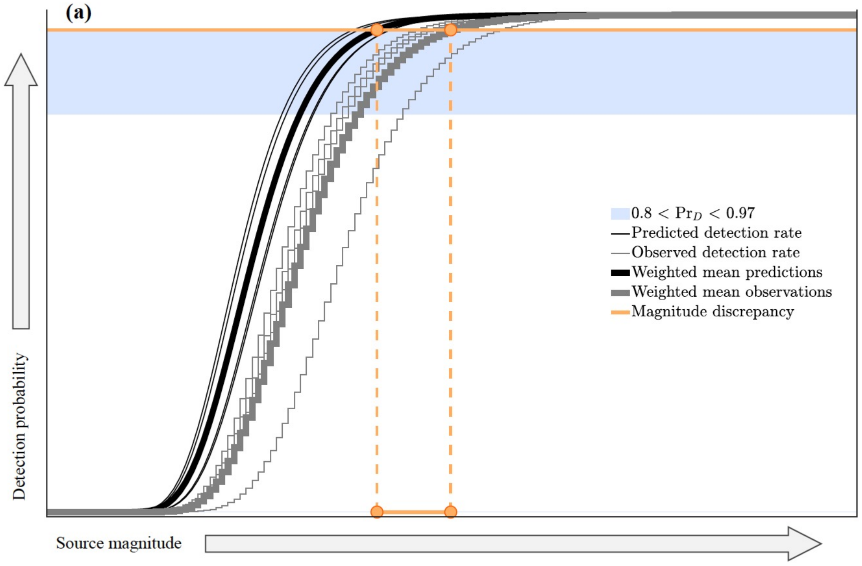
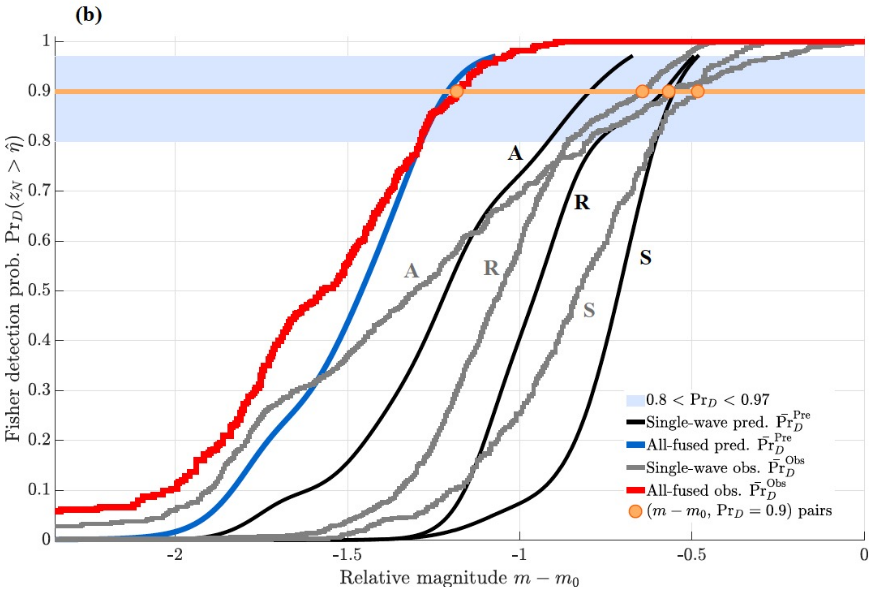
RESULTS (1/2)



(a) A hypothetical predictive detection curve plots detection probability for a given signature against source magnitude. The disagreement between any two points on curves of constant detection probability quantify the magnitude discrepancy. This discrepancy is a simple measure of **predicted** versus **observed** source size disagreement for that particular detection probability.



(b) The fused radio (R), acoustic (A) and seismic (S) data empirically out-performs all other detectors in the detection band of interest (red curve). The error-weighted, time-averaged observed performance curve closely matches its associated predicted performance curve (blue curve). Magnitude discrepancies (orange circles) between 12-day detection averages are smallest for the three-signature fused Fisher detector.

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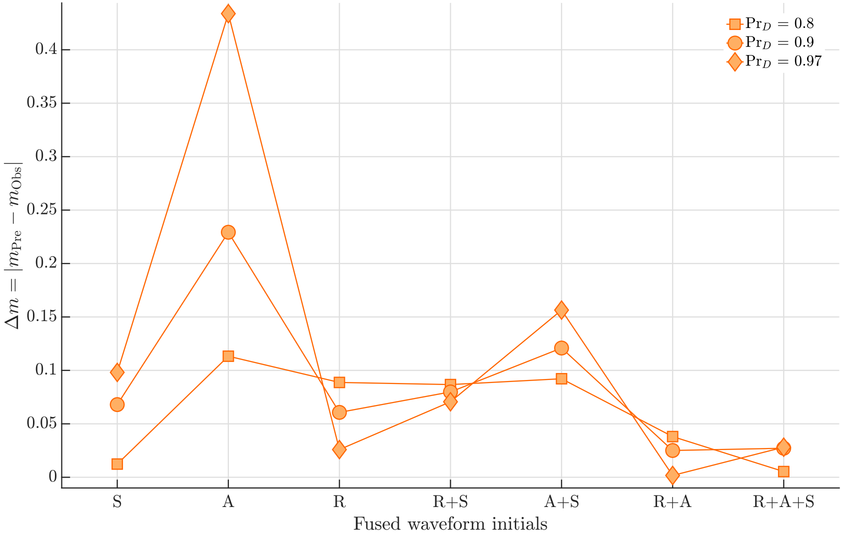
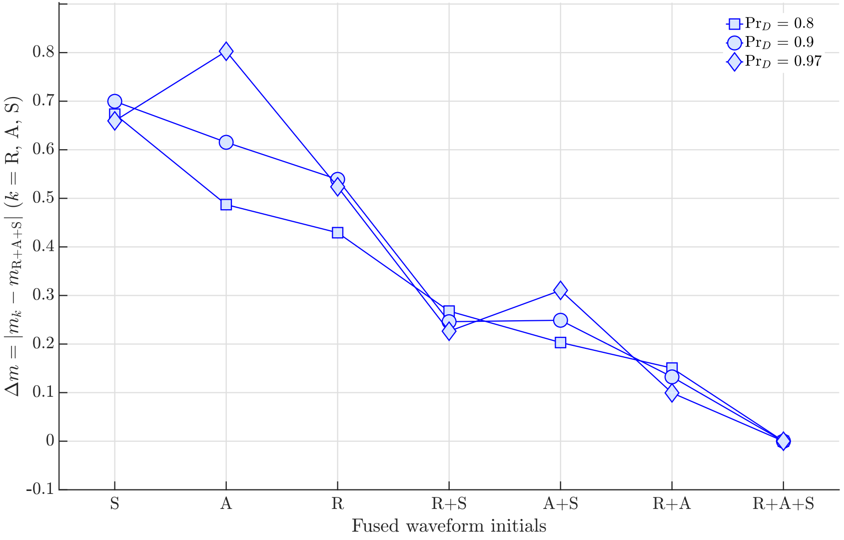
RESULTS (2/2)





The predictive capability of seven Fisher detectors and their threshold magnitudes, at three probability values, against signature type. **Left**: The magnitude discrepancy between observed and predicted detection curves compared against fused statistic type (S = seismic, A = acoustic, R = radio), for three probability values $\Pr_D = 0.8, 0.9, 0.97$. **Right**: The difference in relative magnitude (Δm_k, $k = \mathrm{R}, \mathrm{A}, \text{or } \mathrm{S}$) at which a Fisher detector empirically identifies an explosion waveform statistic, when compared the relative magnitude a Fisher detector that fuses radio, acoustic, and seismic data ($\Delta m_{\mathrm{R+A+S}}$) empirically identifies the same explosion. The three-signature fused Fisher detector shows the greatest observed improvement in magnitude discrepancy over any single signature. These data quantify relative threshold magnitudes for the different Fisher detectors.

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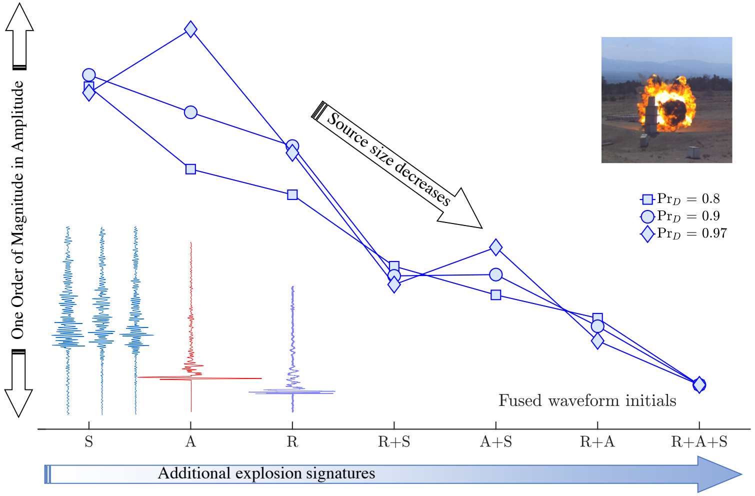
CONCLUSIONS (1/2)

Fusion Reduces Thresholds, Variability, and Provides a Predictive Capability

Our work provides three contributions to our research goals to exploit more physical signatures of explosions, while predictively improving the performance of the signal detection monitoring function:

1. We build a generalized theory for Fisher's Method to fuse and detect signatures output by the same explosion source
2. We improve detection rates for small explosion sources when compared to constituent detectors (**right**), and at reduced false alarm rates
3. Our fused detector shows an improved *predictive capability* to detect explosion sources, when compared to that of single signature detectors

This work further addresses how building compound signals from multiple signatures with high noise contamination provides an increased monitoring capability. In summary, we reduced thresholds, reduced false alarms, increased detection rates, and improved our ability to **predictively** detect signals from explosions.



The smallest explosion yield that various waveform detectors can identify (vertical axis), compared to explosions that our fused detectors can identify. These fused detectors combine radio (**R**), acoustic (**A**), and seismic (**S**) data streams from the same explosion. The three-signature fused detector shows the greatest decrease in monitoring threshold (right data points) and our algorithm's ability to detect smaller explosions, at the same false positive rate. *This fused detector further reduces detection variability.*

Publications

Carmichael, J., Nemzek, R., Symons, N., & Begnaud, M. (2020). A method to fuse multiphysics waveforms and improve predictive explosion detection: theory, experiment and performance. *Geophysical Journal International*, *222*(2), 1195-1212.

Carmichael, J. D., Nemzek, R., Arrowsmith, S., & Sentz, K. (2016). Fusing geophysical signatures of locally recorded surface explosions to improve blast detection. *Geophysical Journal International*, *204*(3), 1838-1842.

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CONCLUSIONS (2/2)

Remarks on Assumptions for the Correlation Detector

Our algorithm parameterizes sample correlation ρ_0 by relative source magnitude $m - m_0$. A source with absolute magnitude m_0 produces the template waveform, and sources with absolute magnitude m produce the target waveform. For *underground explosions*, the target waveform amplitude A relates to relative source magnitude through:

$$A = 10^{m-m_0} A_0.$$

The relative yield between two such *underground explosions* similarly relates to magnitude linearly:

$$10^{m-m_0} = \frac{Y^{\alpha}}{Y_0^{\alpha}}.$$

Our limited waveform correlation comparison between the 4m HoB shots suggests that the relative amplitude scaling still works for *aboveground shots* too (**right**). We conclude that the waveform similarity assumptions on amplitude scaling required for correlation detectors apply to near-surface aboveground shots.