Detecting presence of low SNR emission sources
Analysis and “analysis” vs deep learning

Peter Kuchment, Various parts joint with M. Allmaras, W. Baines, R. Carroll, D. Darrow, Yu. Hristova, G. Kanschat, L. Kunyansky, B. Mallick, A. Olson, J. Ragusa, F. Terzioglu
Supported by DHS, NSF, and Texas A&M grants

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References

- W. Baines, P. Kuchment, and J. Ragusa, Deep Neural Network For Source Detection in 2D High Noise Emission Type Problems, in preparation, 2019
Emission imaging and detection

Goal: Imaging/detection of presence of emission sources. SPECT medical imaging, border crossings and harbors detection.

Direction sensitive sensors are needed.

Issue: Low, up to extremely low (1%, .1%, or even less) SNR.
Anger camera

Standard collimated (Anger) $\gamma$-camera

Kills the signal when SNR is low!
Compton cameras & analogues

Compton $\gamma$-camera

Measures integrals over cones (a lie when the counts are low). Analogs for neutron detectors.
Cone transforms, their properties and inversions

Overdetermined problem - GREAT!

Beautiful (not fully completed) analysis: uniqueness, inversion, stability, microlocal, ...).
Problem formulation

For HS problems the SNR is extremely low. Integral geometry formulations are wrong. Inversion formulas thus are also wrong. Silver lining: one does not need an image, just DETECTION of presence (YES or NO).

**Goal:** Detect presence of a low SNR $\gamma$- or neutron source using Compton-type data.

Possible approaches:
1. Using apriori information and math+stat processing. The backprojection technique below. Works for SNR down to $0.1\%$ for a sufficiently long observation. Too long for neutrons.
2. Bayesian technique
3. Deep learning technique without any prior math processing
Statistical backprojection approach

1. Assume small size of the source.
2. Backproject the (conical) data.
3. Subtract the mean
4. Find statistically significant local accumulations.
Details of the backprojection approach

$N$ - the number of the background particles.

$n$ - number of ballistic particles from the source.

$SNR := n/N$.  $T := N + n$

$p$ the (relative to the cargo hold) size of the source.

Apply (incorrectly, but justified by numerics) a CLT to get the detectability estimate

$$T \sim \left( \frac{8}{SNR} \right)^2 p(1 - p)$$

Results are similar with Bayesian techniques (with no location detection).
<table>
<thead>
<tr>
<th>Analysis</th>
<th>Low SNR: “analysis” + white magic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black magic</td>
<td></td>
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</tbody>
</table>

## Experiments

Table: Vertical - SNR in %. Horizontal # of ballistic particles (1000 source particles @ SNR = 1% \( \Rightarrow T = 101,000 \).

<table>
<thead>
<tr>
<th>dist &lt; 3( d )</th>
<th>100</th>
<th>68.129</th>
<th>46.196</th>
<th>31.623</th>
<th>21.544</th>
<th>14.678</th>
<th>10</th>
<th>6.812</th>
<th>4.543</th>
<th>3.162</th>
<th>2.154</th>
<th>1.467</th>
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Cargo effects

In the case of $\gamma$ detection, presence of complex cargo causes problems.

The SNR (for ballistic source particles) drops to undetectable by the backprojection methods levels.
However,

**Figure**: Material Arrangement
Analysis

Low SNR: “analysis” + white magic
Black magic

Is there some information?

Figure: Grid with 4 detectors at various SNR

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Could deep learning help?
## Results comparisons - no cargo

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<thead>
<tr>
<th>Bkgnd Cnt</th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>.960/.909</td>
<td>.998/.644</td>
</tr>
<tr>
<td>5000</td>
<td>.949/.725</td>
<td>.882/.528</td>
</tr>
<tr>
<td>2000</td>
<td>.732/.530</td>
<td>.519/.510</td>
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**Neural Network Performance SNR 2% / 1%**

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**Back Projection Performance SNR 2% / 1%**

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Deep learning with cargo

- Convolutional Neural Network (CNN) is trained on 750 simulated media configurations with randomly placed source. Architecture is shown in Fig. below.
- Outputs a probability measure $P$ on $\{0, 1\}$, a source is determined to be present if $P(x = 1) > 0.5$.
- High Exposure Network (HEN) is trained on simulations corresponding to higher exposure time. Low Exposure Network (LEN) is trained on simulations corresponding to lower exposure time.
CNN architecture used for source detection. The left-most cell shows an example of the detector data input to the CNN.
Radiative transfer equation (RTE):

\[ \hat{u} \cdot \nabla \psi(\vec{r}, \hat{u}) + \sigma_t(\vec{r}) \psi(\vec{r}, \hat{u}) = \]

\[ \frac{\sigma_s(\vec{r})}{4\pi} \int_{S^2} \psi(\vec{r}, \hat{u}') \cdot d\hat{u}' + \frac{Q(\vec{r})}{4\pi} \]

(1)

\( \psi \) – angular flux, \( Q \) – volumetric source term, \( \sigma_t \) and \( \sigma_s \) - the total cross section and scattering cross section respectively (isotropic).
### Results comparisons - randomly generated cargo

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<th>Exposure Time (s)</th>
<th>Sensitivity</th>
<th>Specificity</th>
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<tbody>
<tr>
<td>30</td>
<td>1.00/.96</td>
<td>.97/.77</td>
</tr>
<tr>
<td>20</td>
<td>.97/.65</td>
<td>.99/.86</td>
</tr>
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<td>10</td>
<td>.69/.66</td>
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Performance at 1% SNR. (HEN / LEN)

The end