Detecting presence of low-emission radiation sources

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Emission imaging and detection

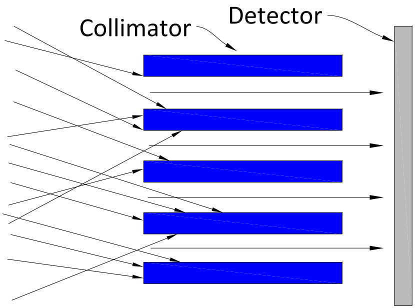
Goal: Imaging/detection of presence of emission sources.
SPECT medical imaging, border crossings and harbors detection.

Direction sensitive sensors are needed: compare dimensions of the observation boundary and the interior.

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

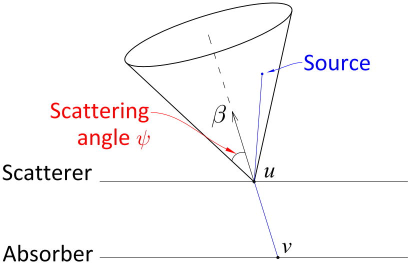
Direction detection: Anger camera

Standard collimated (Anger) γ-camera



Kills the signal when SNR is low!

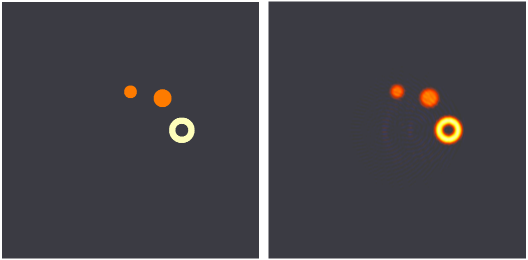
Compton γ-camera



Measures integrals over cones (a lie when the counts are low).
Analogs for neutron detectors.
Overdeterminacy: $3D$ in $2D$, $5D$ in $3D$

Cone transforms, their properties and inversions

Overdetermined problem - GREAT!



3D SPECT reconstructions with noise

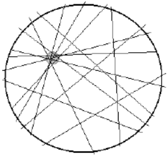
Survey: F. Terzioglu, P. Kuchment, and L. Kunyansky, Compton camera imaging and the cone transform : A brief overview, *Inverse Problems*, **34** (2018), No. 5, 054002.

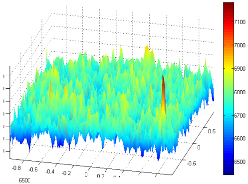
Problem formulation

In HS problems – SNR is extremely low.
Integral geometry formulations are wrong.
Inversion formulas thus are also wrong.
Silver lining: no image needed, just DETECTION of presence (YES or NO).
Goal: Detect presence of a low SNR γ- or neutron source using Compton-type data.
Approaches:
1. A **backprojection technique:** Using apriori information and math+stat processing. Works for SNR down to .1%
for a sufficiently long observation. Too long for neutrons.
2. **Deep learning technique** without any prior math processing

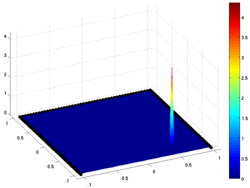
The idea of backprojection method

1. Assume a small size of the source.
2. Backproject the (conical) data.





3. Find statistically significant local accumulations.



Details of the backprojection approach

Applying CLT and some (incorrect) independence assumptions, get the detectability estimate

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

Here N - # of background particles.
n - # of ballistic particles from the source.
$SNR := n/N$. $T := N + n$
p the (relative to the cargo hold) size of the source.
High specificity is built in!

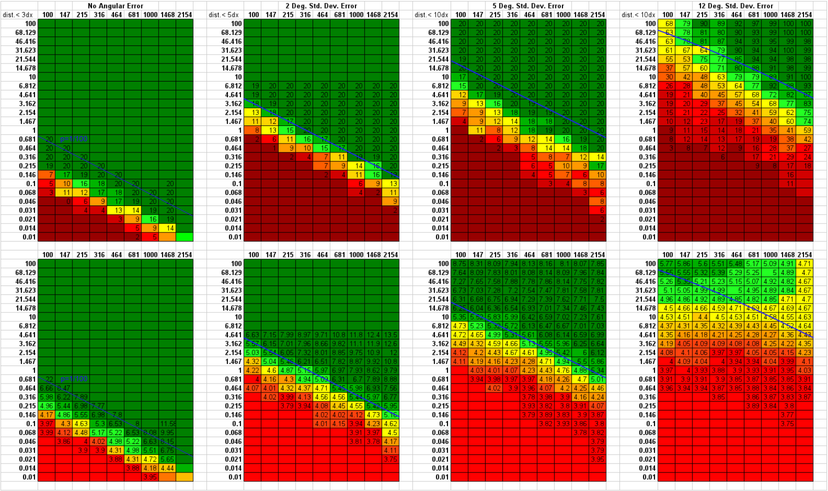
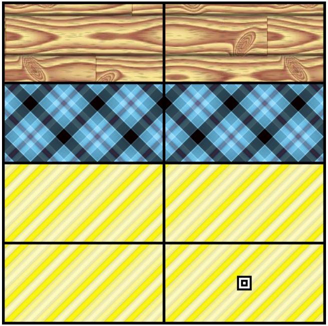
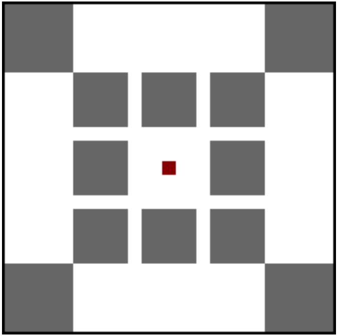


Figure: Vertical - SNR in %. Horizontal # of ballistic particles (1000 source particles @ SNR = 1% $\Rightarrow T = 101,000$.)

References for the technique

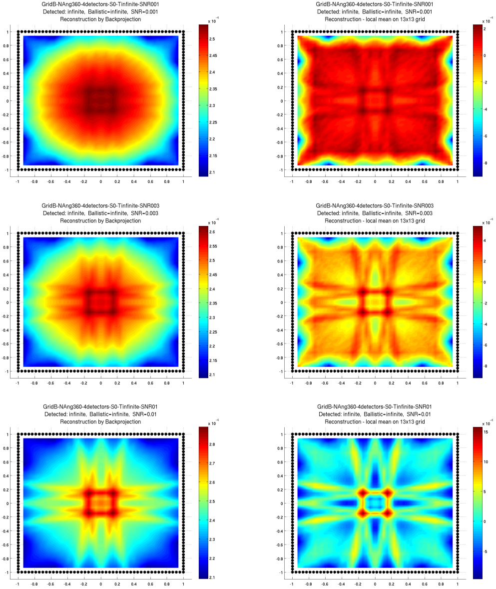
- X. Xun, B. Mallick, R. Carroll, P. Kuchment, Bayesian approach to detection of small low emission sources, *Inverse Problems* **27** (2011), 115009
- M. Allmaras, D. Darrow, Y. Hristova, G. Kanschat, P. Kuchment, Detecting small low emission radiating sources, *Inverse Problems & Imaging*, **7** (1) (2013), 47–79.
- M. Allmaras, A. Ciabatti, Y. Hristova, P. Kuchment, A. Olson, J. Ragusa, Passive Detection of Small Low-Emission Sources: Two-Dimensional Numerical Case Studies, *Nuclear Sci. and Eng.* **184** (2016), no.1.

For γ detection, complex cargo causes problems (less for neutrons, where there are other issues)

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

However, is there some information?



Results comparisons - no cargo

Bkgnd Cnt	Sensitivity	Specificity
10000	.960/.909	.998/.644
5000	.949/.725	.882/.528
2000	.732/.530	.519/.510

Neural Network Performance SNR 2% / 1%

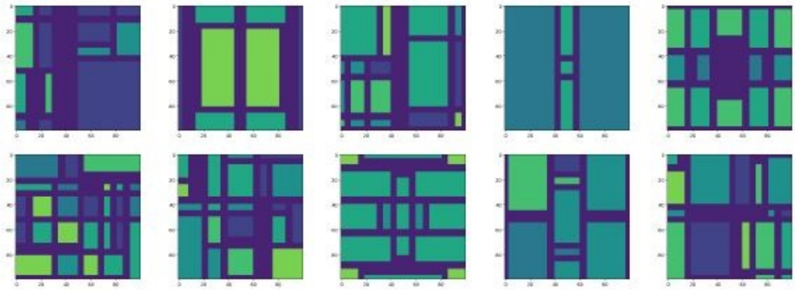
Bkgnd Cnt	Sensitivity	Specificity
10000	.06/.00	1.0/1.0
5000	.06/.00	1.0/1.0
2000	.02/.02	1.0/1.0

Back Projection Performance SNR 2% / 1%

Deep learning with cargo

- Variety of cargo scenarios is produced (with realistic material parameters) for training and testing.
- Forward radiation transport equations are solved numerically (with realistic parameters) to produce training and testing data.
- A convolution (CNN) network trained that outputs a probability measure $\mathbb{P}$ on $\{0, 1\}$, a source is determined to be present if $\mathbb{P}(x = 1) > 0.5$. (also another probability measure detecting the number of sources up to 4).
- The trained network's performance (generalization) is tested.

Examples of cargo scenarios



A selection of cargo configurations

Independent algorithms are used for producing training and testing cargo scenarios.

Radiative transfer equation (RTE):

$$\hat{u} \cdot \nabla\psi(\vec{r}, \hat{u}) + \sigma_t(\vec{r})\psi(\vec{r}, \hat{u}) = \frac{\sigma_s(\vec{r})}{4\pi} \int_{\mathbb{S}^2} \psi(\vec{r}, \hat{u}') \cdot d\hat{u}' + \frac{Q(\vec{r})}{4\pi} \quad (1)$$

ψ – angular flux, Q – volumetric source term, σ_t and σ_s - the total cross section and scattering cross section respectively (isotropic).

Dimensionality

Dimensionality of the data: $144000 = 400 \times 360 \times 1$

Number of Sources	One Detector	Two Adjacent Detectors	Two Opposite Detectors	Three Detectors	Four Detectors	Total
0	6756	6756	3378	6756	1689	25335
1	27024	27024	13512	27024	6756	101340
2	40536	40536	20268	40536	10134	152010
3	27024	27024	13512	27024	6756	101340
4	6756	6756	3378	6756	1689	25335
Total	108096	108096	54048	108096	27024	405360

Number of training samples in each category

Number of Sources	One Detector	Two Adjacent Detectors	Two Opposite Detectors	Three Detectors	Four Detectors	Total
0	6952	6952	3476	6952	1738	26070
1	27808	27808	13904	27808	6952	104280
2	41712	41712	20856	41712	10428	156420
3	27808	27808	13904	27808	6952	104280
4	6952	6952	3476	6952	1738	26070
Total	111232	111232	55616	111232	27808	417120

Number of testing samples in each category

Results comparisons - sensitivity and specificity

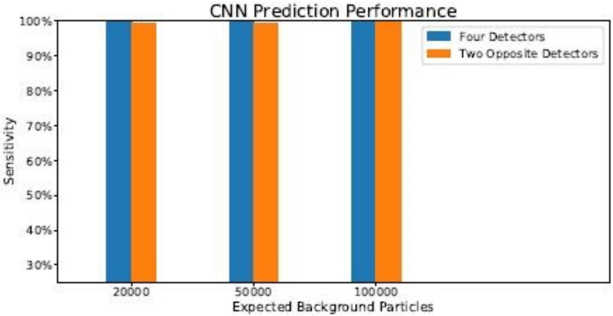
Expected Particle Count	Sensitivity	Specificity
100000	99.90%	99.71%
50000	99.78%	94.59%
20000	99.81%	36.36%

Sensitivity and specificity of the CNN source detection with each source having 1% SNR.

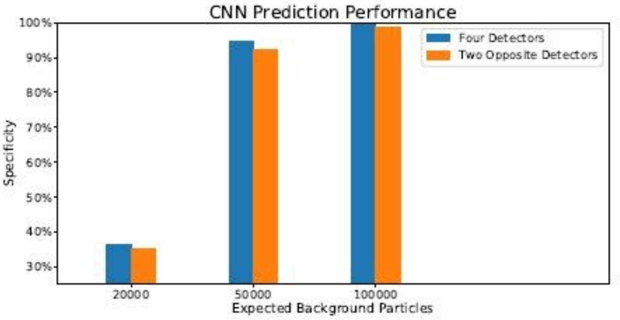
Expected Particle Count	Sensitivity	Specificity
100000	71.04%	99.31%
50000	65.55%	99.31%
20000	52.13%	98.91%

Sensitivity and specificity of the backprojection source detection with each source having 1% SNF

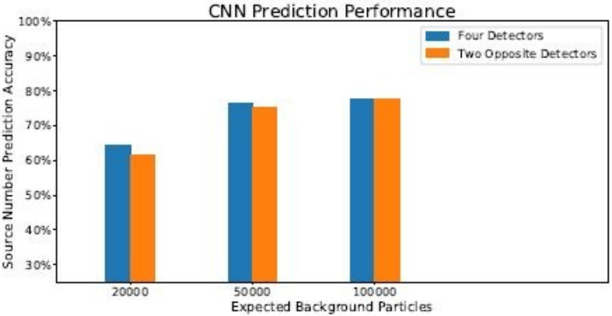
Performance - sensitivity



Performance - specificity



Performance - # of sources



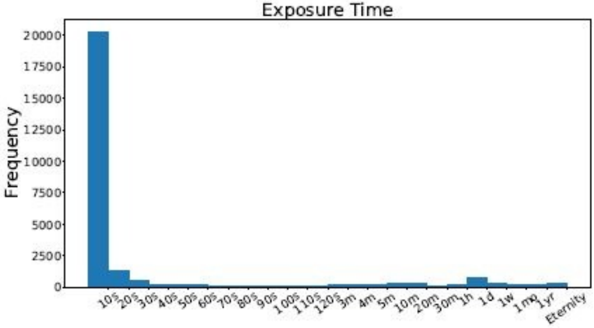
Accuracy of the number of source detection.

Diluted sources

Expected Particle Count	Sensitivity one source	Sensitivity two sources	Sensitivity three sources	Sensitivity four sources	Specificity
100000	99.74%	96.57%	89.67%	82.62%	99.71%
50000	99.68%	97.25%	93.51%	89.13%	94.59%
20000	99.99%	99.95%	99.86%	99.77%	36.36%

Sensitivity and specificity of the source detection techniques with split source strength.

Time till detection



Histogram of the number of runs vs. exposure times required for detection for the testing data set. These times are computed in the case that all four linear detector arrays are present and anywhere between one and four sources are present.

Some further questions

- What are the features discovered?
- More data.
- $3D$
- Real data?
- Can CNN detect the location?
- Using downscattered particles.

Thanks