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Nuclear smuggling is a clear and present danger

Materials

Interceptions

“Law enforcement officials in the US seize only 10 to 40% of the illegal drugs smuggled into the country each year

Russia stops from 2 to 10% of illegally imported goods and illegal immigrants on the border with Kazakhstan”

Total = 1.13 IAEA “significant quantities”
(8 kg Pu or 25 kg of U^{235} in HEU)
Active radiography is an established inspection technique.

To date, radiography has depended on artificial sources of radiation, which bring with them a risk-benefit tradeoff.

1895
First x-ray image
(Mrs. Roentgen’s hand)

2001
Inspection of truck with American Science and Engineering backscatter x-ray system.
Passive Source Radiography: Cosmic Radiation

No artificial radiation means:

1. Cars and trucks inspection without evacuating the driver
   significant time factor
2. Deployment abroad without local regulatory complications
   Detection at point of origine
3. No radiation signal to set off a salvage trigger
   Minimizes inspection risks.

1. Neutrons
2. Neutrinos
3. Electrons
4. Muons
5. Etc.
Cosmic-ray muons

• As cosmic rays strike our upper atmosphere, they are broken down into many particle components, dominated by muons.
• Muons have a large penetrating ability, being able to go through tens of meters of rock with low absorption.
• Muons arrive at a rate of 10,000 per square meter per minute (at sea level).
How Muons Interact with Material

Muons are charged either positive and negative.

High energy: Median 3 MeV

Two modes of interaction:
- Absorption
- Coulomb Scattering
Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

Luis Alvarez, 1950
Muon mapping of Chephren’s Pyramid

“Search for Hidden Chambers in the Pyramids”
Luis W. Alvarez *et al.*

*Alvarez et al. used only absorption, not scattering*

Successful experiment - existence of hidden chamber ruled out

- actual image with no hidden chamber
- simulated image with hidden chamber like the one in Cheops’ pyramid
Shadowgrams (from scattering)

Possible to get shadowgrams from scattering instead of absorption

Proton radiography
Basic Concept of Multiple-Scattering
Muon Radiography

- Track individual muons (possible due to modest event rate).
- Track muons into and out of an object volume.
- Determine scattering angle of each muon.
- Infer material density within volume from data provided by many muons.
Scattering is Material Dependent

![Graph showing radiation length and mean square scattering for various materials.]

- Water
- Plastic
- Concrete
- Aluminum (Z=13)
- Iron (Z=26)
- Copper (Z=29)
- Lead (Z=82)
- Tungsten (Z=74)
- Uranium (Z=92)

For 3 GeV muons:

- Radiation Length (cm)
- Mean Square Scattering (mrad²/cm)
Prototype Los Alamos instrument

- Tungsten Block
- Scintillator (temporary trigger)
- Chamber 1
- Chamber 2
- Chamber 3
- Chamber 4
- Muons
Reconstruction – Localizing Scattering

- Assume multiple scattering occurs at a point.
- Find point of closest approach (PoCA) of incident and scattered tracks.
- Assign (scattering angle)$^2$ to voxel containing PoCA.
- Since detectors have known position uncertainty, signal may be spread over voxels relative to PoCA uncertainty.
- Simply add localized scattering signals for all rays.
Maximum Likelihood Image Reconstruction

Use single layer probability model to calculate the contribution of voxel $j$ to the observed displacement of ray $i$.

Develop a model of the unknown object that maximizes the likelihood that we would observe what we actually observed.

E-M works well:

Can handle large voxelization
Compute as data comes in
First Muon Radiograph
Radiograph of another object
Clamp in z-projections
Objects
1x1x1 m³ Fe box (3 mm walls)
Two half density Fe spheres (automobile differentials)

ML reconstruction
1 minute exposure; with U sphere

ML reconstruction
1 minute exposure; No U sphere

Shielding of SNM works to our advantage!
Maximum Likelihood Tomographic Reconstruction
28x28x64 voxelation, 1 minute simulated data

3-D Perspective View

Side View

Top View

U in empty container

U in distributed Fe

U and car differentials

Calculation time: ~2 min on a 3 GHz single-processor Windows PC
Real data from drift tubes.

Cylindrical Drift Tube Geometry

- High E field at 20 μm wire causes gas avalanche multiplication
- $e^-$ Drift Time $\cong 20 \text{ ns/mm} \times R$ in gas: $0 \leq \Delta T \leq 500 \text{ ns}$
- Radius of closest approach given by $\Delta T$ and saturated drift velocity $v_d$.
- Spatial resolution goal $\leq 0.4 \text{ mm}$

Representative Anode Signal

- Low count rate ($\sim \text{kHz}$) and multiplicity
  $\Rightarrow$ Relatively large cell size allowed:
  $D \sim 2 \text{ inch}$
- Larger cell size $\Rightarrow$ fewer channels
Drift tubes for muon tracking

- Potentially low cost
- No fancy materials
- Detector built from:
  - aluminum tubes
  - tungsten wire
  - argon gas

\[ \text{Drift tracking equation} \]

\[ Z = \Delta Z \]
Modules combined into Muon Tracker

- Drift tube detectors
- 4 x-y planes
- 128 tubes per x or y
  - 1024 channels total
- Reconfigurable

EOY 2004 Goal: 40 modules, 64” x 64” active area with good solid angle
Large Muon Tracker
Momentum Estimation

- Measuring particle momentum increases confidence in material inference.
- One method is to estimate momentum from scattering through known material.
- With 2 plates, $\Delta p/p$ is about 50%.
- With $N$ measurements, $\Delta p/p$ approaches:

$$\sqrt{\frac{1}{2N}}$$
Bonus Material
Absorbtion

Data: \[ Z_i = \begin{cases} 1 & \text{Absorbed} \\ 0 & \text{Not} \end{cases} \]

Stoppage \[ S = \int \rho(\gamma(s))ds \]

Problem: Different physics for stoppage Than scattering. Can We really combine data?

Model \[ P[Z = 1 \mid S = s, E = e] = G(s - e) \]

Are planning experiments to estimate H

\[ P[Z = 1 \mid S = s] = \int G(s - e)F(de) = H(s) \]

Nice little inverse problem
Knock off electrons and Bremsstrahlung confuses the drift tubes (~5%)
Modeling Muon Scattering

Data from scattered muons:
- Change in position \( \Delta x \)
- Change in angle \( \Delta \theta \)

Inverse problem with the signal in the variance

\[
E[\Delta \theta] = E[\Delta x] = 0
\]

\[
Var[\Delta \theta] \propto \frac{1}{p^2} \frac{L}{L_{\text{rad}}}
\]

Material specific parameter \( \lambda \)

Momentum (unknown)
**Point of Closest Approach (PoCA)**

**Original Approach (2003)**

Assumes that the scattering took place at the point where the incoming and outgoing paths come closest.
Slices through reconstructed volume
Ray-crossing algorithm cuts clutter

No contraband

3 uranium blocks (20 kg each)

10 tons of distributed iron filling the container
Clustering algorithms to automatically search for dense objects

- Look at significantly scattered muons
- If high-Z object present, inferred locations of scattering will “cluster”
- Cluster centroids are considered the candidate locations for a threat object, and passed to a classifier

Input to simulation:
Shipping container full of automobile differentials & one uranium sphere

Identified clusters, including the real one
Candidate clusters can be tested with a “machine-learned” algorithm

**Breakthrough:** Algorithm has found a good set of features based on statistics of a local, 27-voxel cube

**Result:** Low error rates for two-minute exposures
Single layer model

Observations: \((\theta_i, \Delta \theta_i, \Delta x_i)\). Conditionally on \(\theta_i = 0\),

\[
D_i = \begin{pmatrix} \Delta \theta_i \\ \Delta x_i \end{pmatrix} \sim \mathcal{N} \left( 0, \frac{\lambda}{p^2} \begin{pmatrix} \frac{L}{2} & \frac{L^2}{2} \\ \frac{L^3}{3} & \frac{L^2}{2} \end{pmatrix} \right).
\]

If \(\theta_i \neq 0\), distribution of \(D_i|\theta_i\) is approximatively mean zero Gaussian with variance-covariance

\[
\frac{\lambda}{p^2} \begin{pmatrix} \frac{L \tan \theta_i}{2} & \frac{(L \tan \theta_i)^2}{2} \\ \frac{(L \tan \theta_i)^2}{3} & \frac{(L \tan \theta_i)^3}{2} \end{pmatrix} = \frac{\lambda}{p^2} \Sigma_{\theta_i}
\]

- Parameter \(\lambda\) specific of material.
- Site specific distribution of momentum \(p\) known.

\text{Model path as an integrated Brownian motion}
An Identifiability Surprise

\[ \Delta \theta = \sum_j \Delta \theta_j \quad \Delta x = \sum_j \Delta x_j + R_j \Delta \theta_j \]

\[ E[\Delta \theta_j] = E[\Delta x_j] = 0 \]

Lemma 1: Parameter identifiable if three or less homogeneous layers.

Lemma 2: In voxelized volume, parameters are identifiable.

Function of the path length in each layer