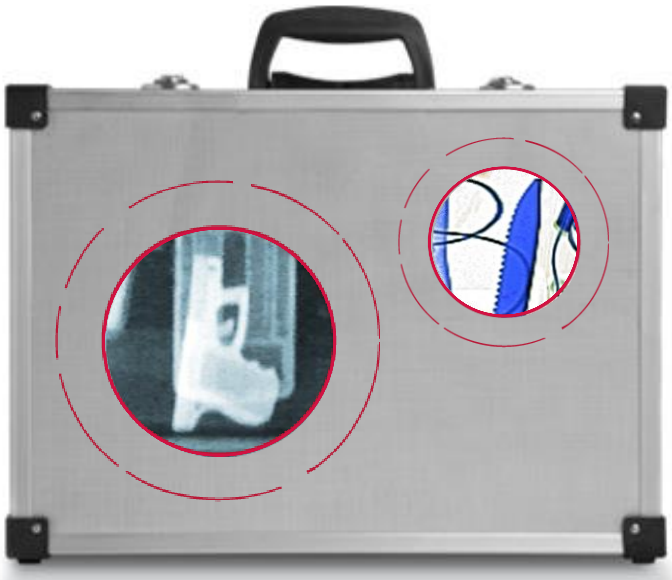


Scatter Attenuation Tomography (SAT):
A Novel X-Ray Technique for Material Identification

Peter Rothschild, Paul Bradshaw, Martin Rommel, Lou Wainwright

American Science & Engineering

AS&E
Detect the difference.

Preview of Conclusions

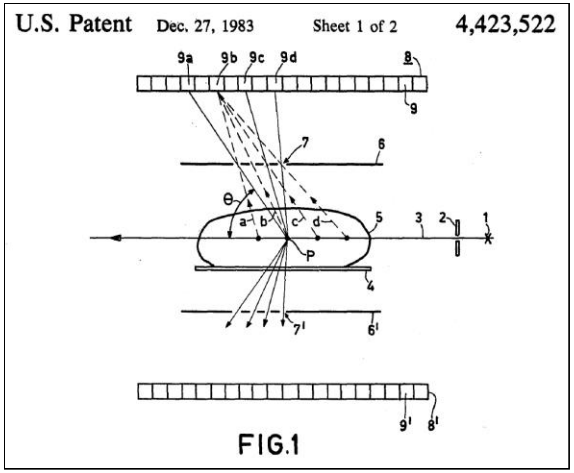
- SAT is a powerful new x-ray technique for identifying concealed materials
  - Very robust to surrounding clutter
  - Highly specific (sensitive to both density and atomic number)
  - Beam hardening effects can be easily corrected for
  - Well suited to screening liquids or solids
- SAT is a point interrogation method better suited to individual items or level 2 inspection
  - Acquisition times are typically on the order of 1-5 seconds per interrogation
  - Level 1 screening applications for baggage would require fairly intense x-ray sources

HOW CAN WE USE INCOHERENT (COMPTON) SCATTER OF X-RAYS TO CHARACTERIZE OR IDENTIFY CONCEALED MATERIALS?

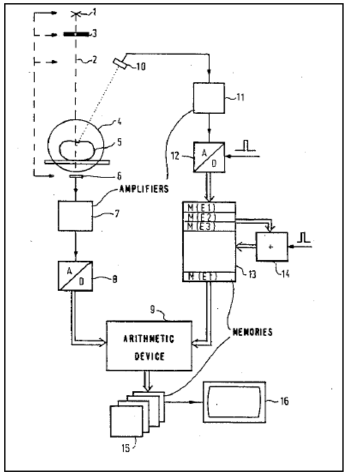
AS&E®
Detect the **difference.**

Prior Art (with Monochromatic Sources)

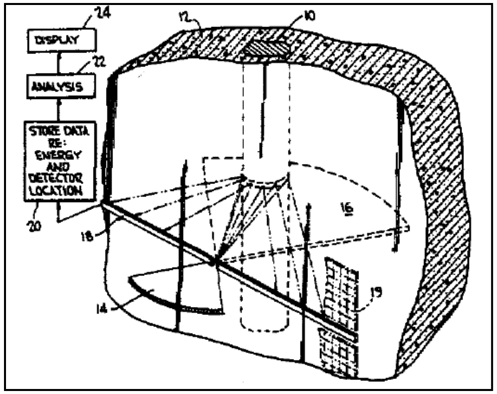
G. Harding; Philips, 1983



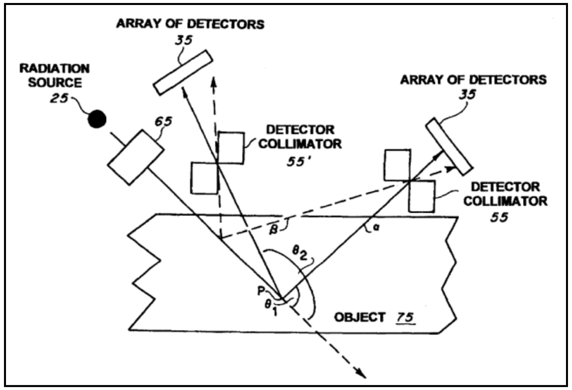
G. Harding & J.M. Kosanetzky; Philips, 1989



S. Norton; U.S. Dept. Commerce, 1995

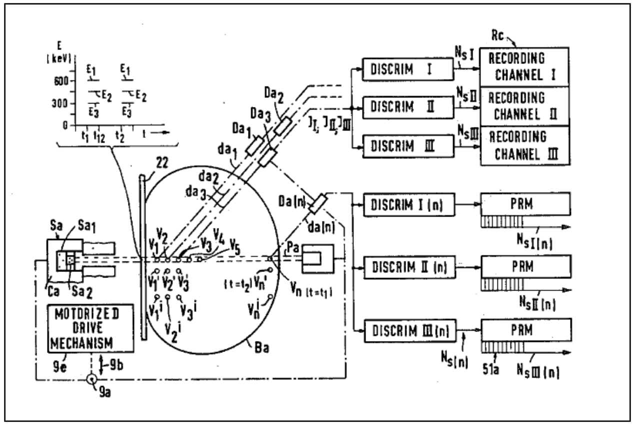


Y.S.Ham; Korean Atomic Energy R.I., 1998

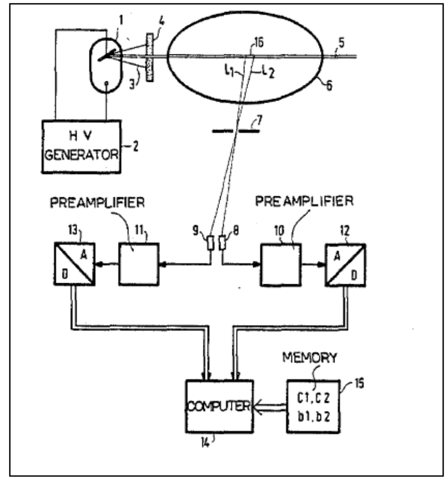


Prior Art (with X-Ray Tubes)

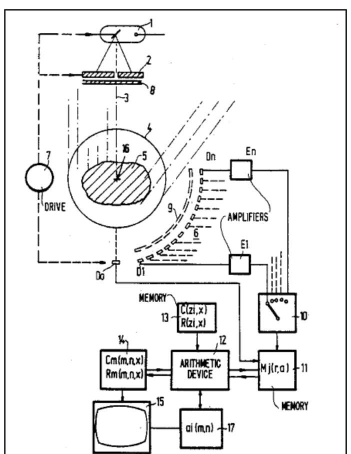
K.H. Reiss & K. Killig; Siemans, 1978



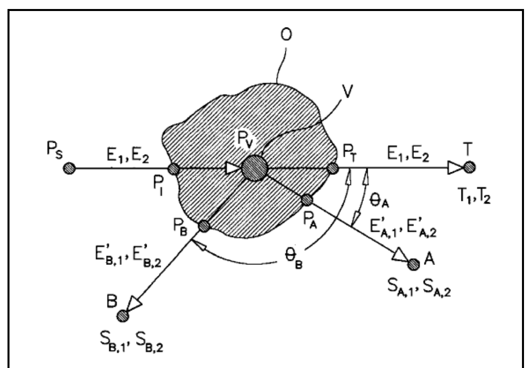
G. Harding; Philips, 1988



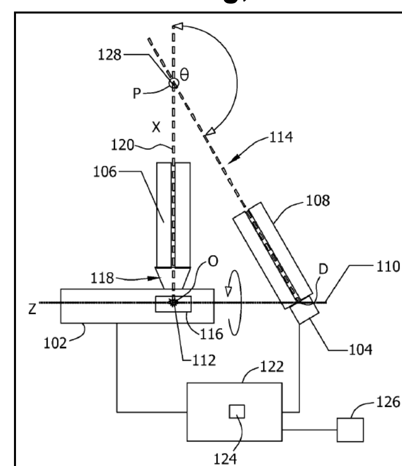
G. Harding & J.M. Kosanetzky; Philips, 1989



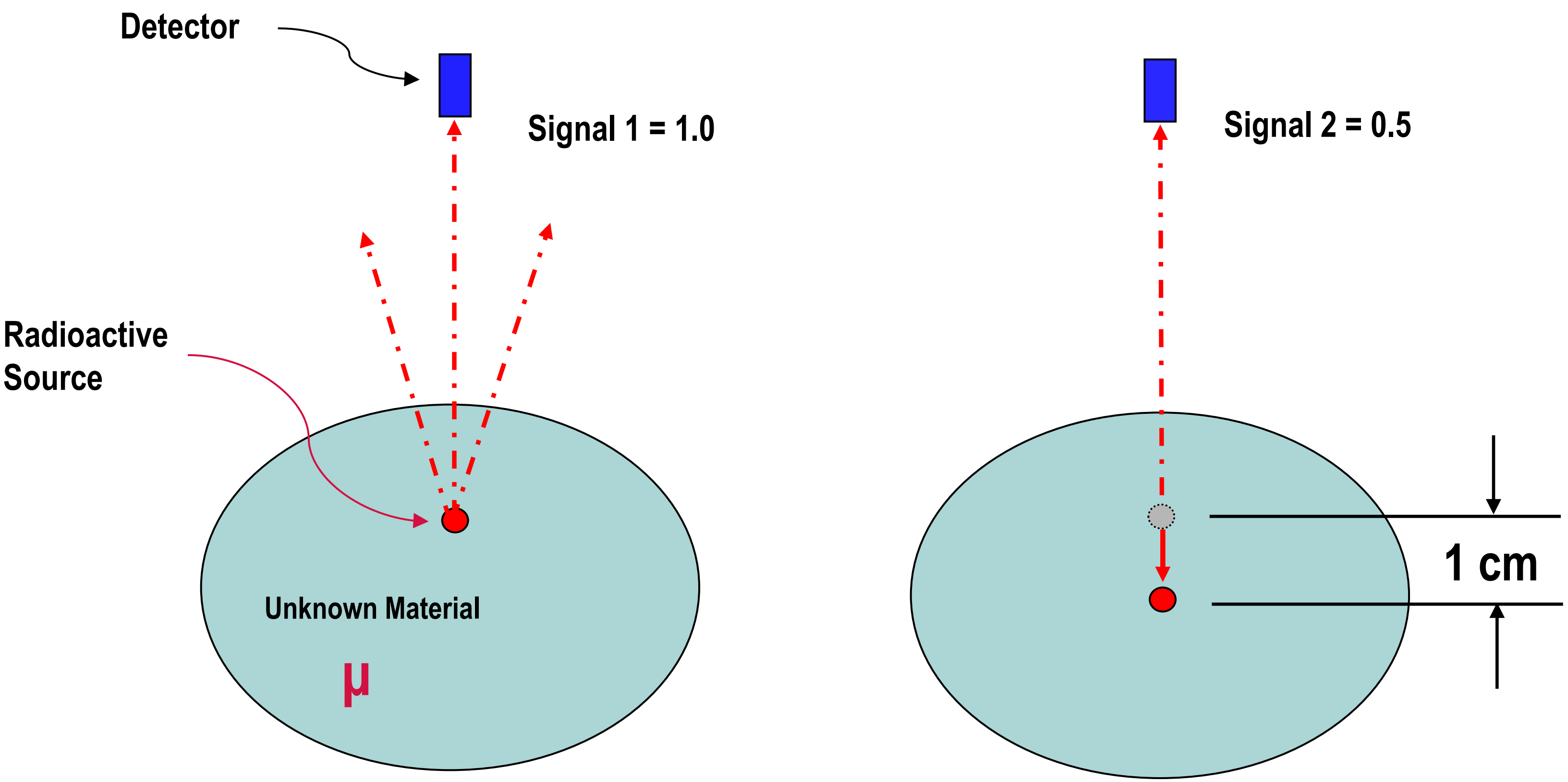
E. Hussein & B. Achmad; Univ. New Brunswick, 2003



G. Harding; 2011

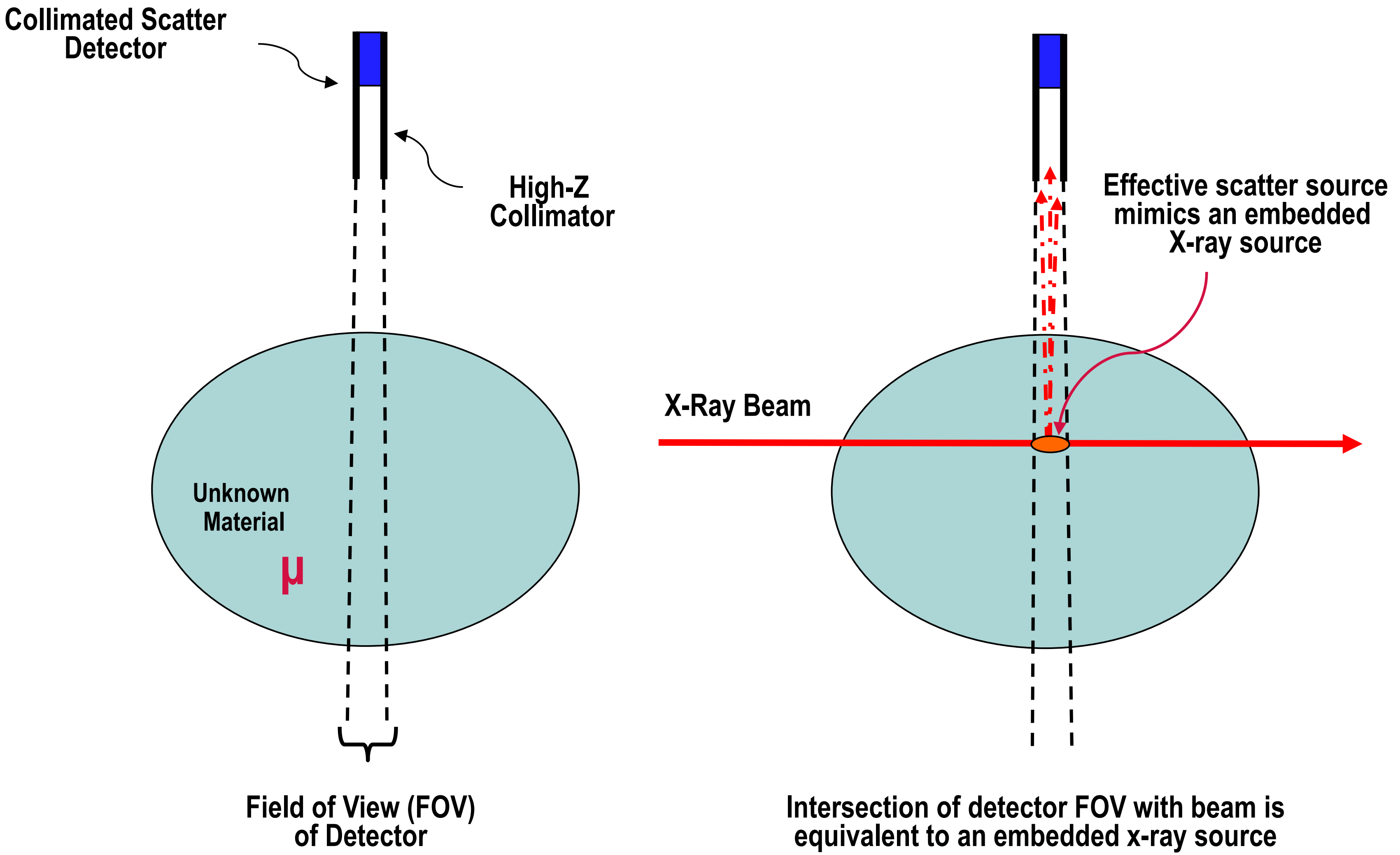


"Thought Experiment" with an Embedded Radioactive Source



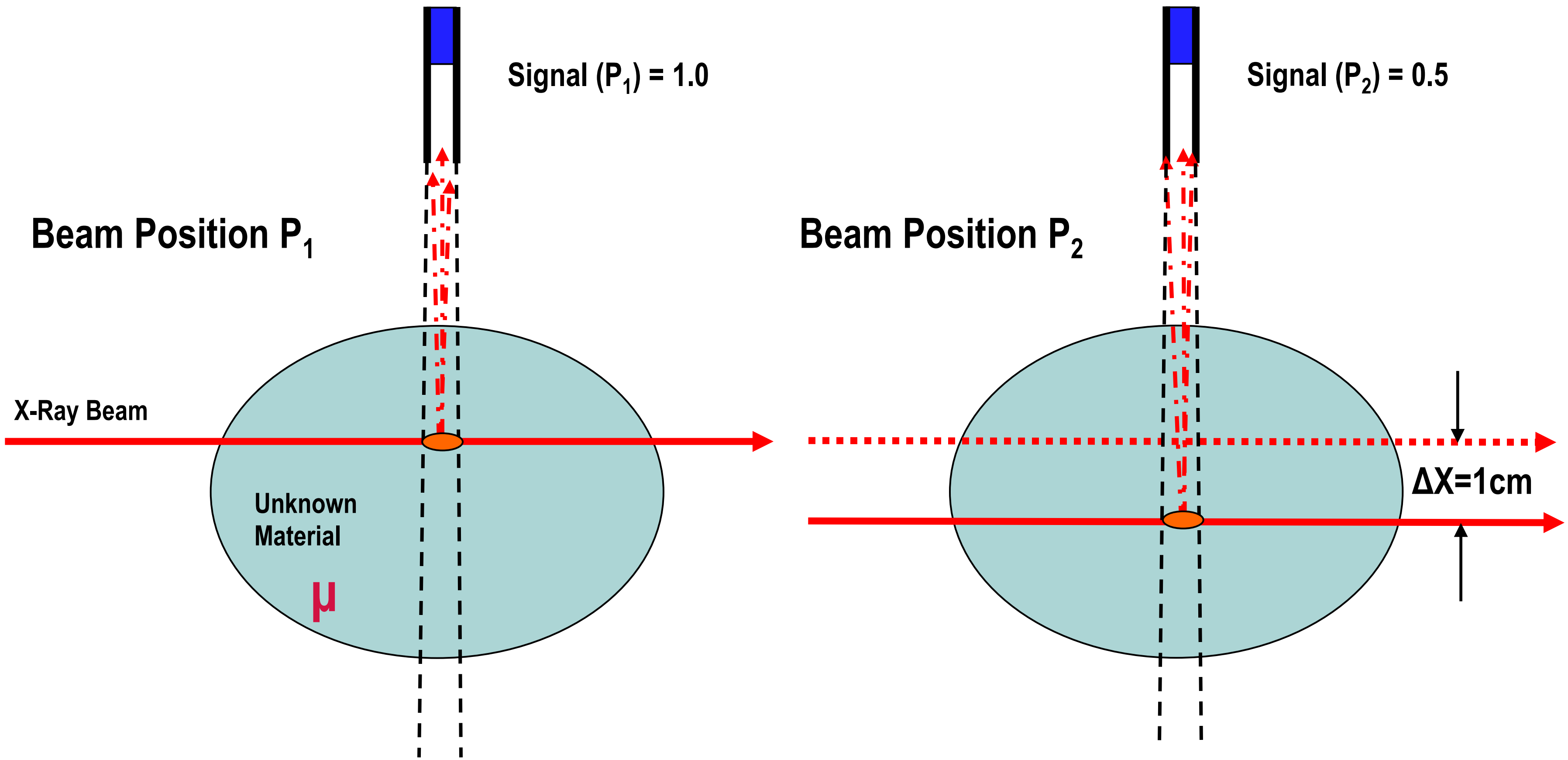
$$\text{Atten Coeff} = \mu = \frac{\Delta(\text{Signal})/\text{Signal}}{\Delta X} = 0.5/\text{cm}$$

Collimated detector with an X-Ray beam can mimic an embedded X-Ray source



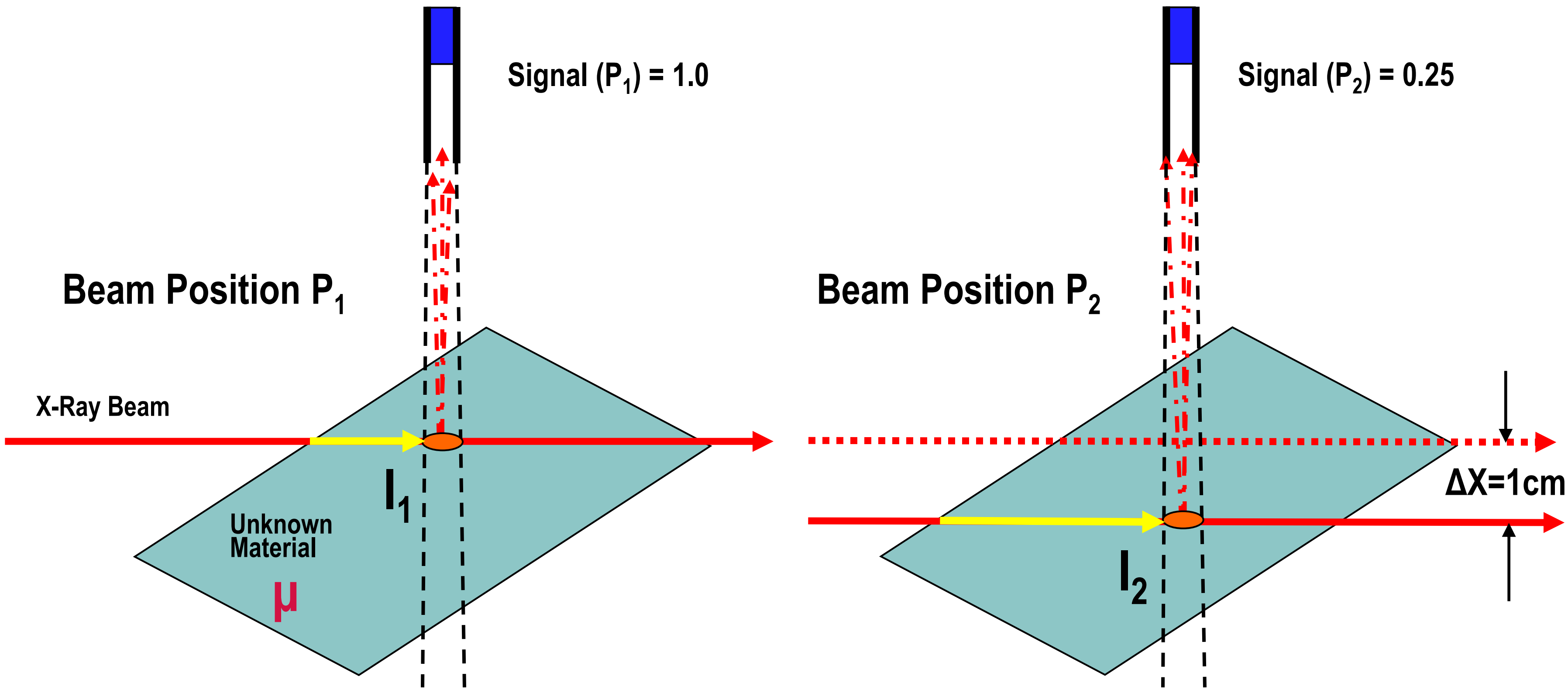
Moving the X-Ray beam is equivalent to moving the embedded source

AS&E



$$\text{Atten Coeff} = \mu = \frac{\Delta(\text{Signal})/\text{Signal}}{\Delta X} = 0.5/\text{cm}$$

However, there is a problem… we assumed the source strength does *NOT* vary with time

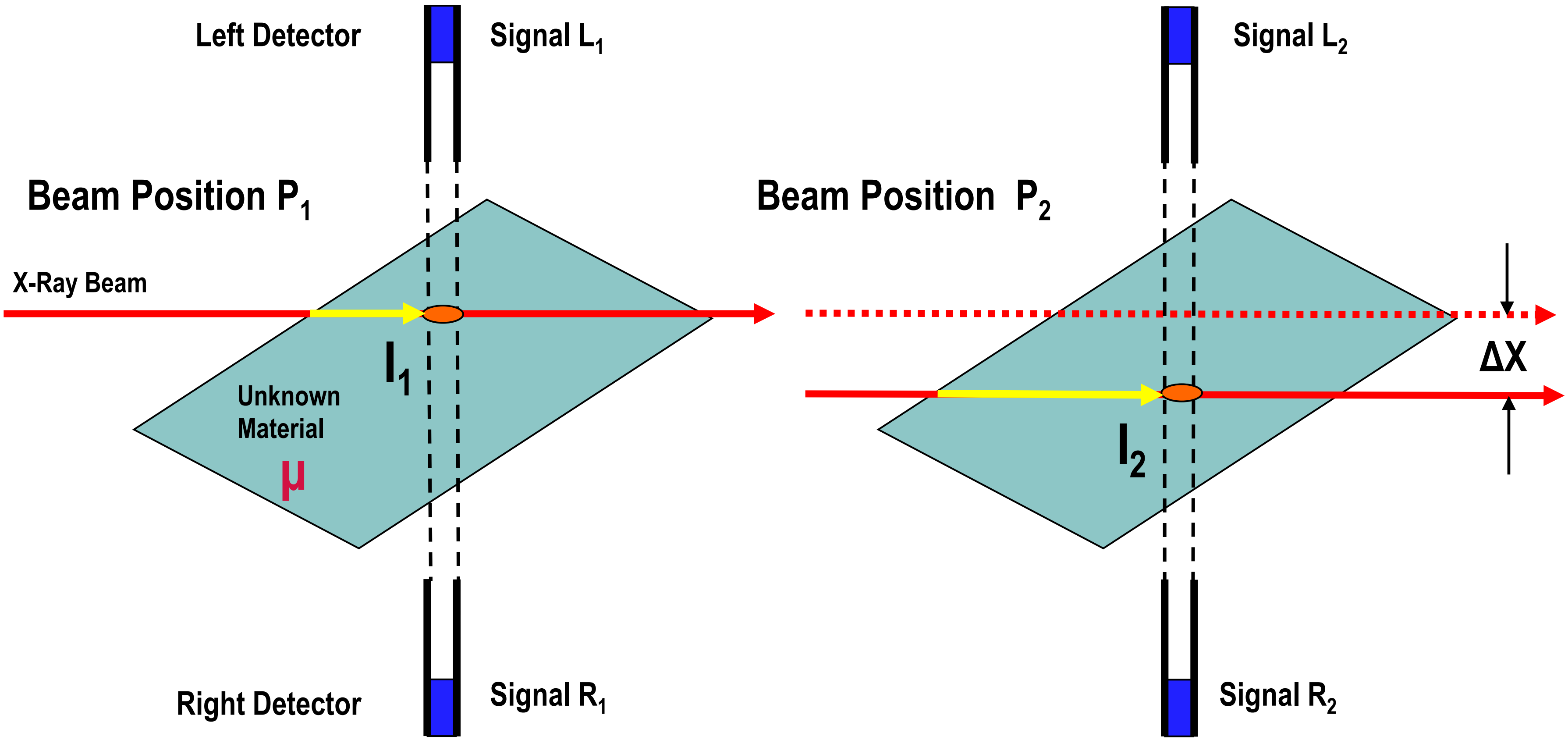


$I_2 = I_1 / 2 \longrightarrow$ Scatter source at time t_2 is <u>weaker</u> than at t_1

$$\text{Atten Coeff} = \mu = \frac{\Delta(\text{Signal})/\text{Signal}}{\Delta X} = 0.75/\text{cm}$$

(Incorrect!)

Solution: Use two detectors



$$L_1 = I_1\, \rho_e\, V_N \Delta t_1\, d\Omega_L \qquad R_1 = I_1\, \rho_e\, V_F \Delta t_1\, d\Omega_R e^{-\mu\Delta x}$$

$$L_2 = I_2\, \rho_e\, V_F \Delta t_2\, d\Omega_L e^{-\mu\Delta x} \qquad R_2 = I_2\, \rho_e\, V_N \Delta t_2\, d\Omega_R$$

Take Ratios of Signals in Each Detector:

$$\frac{L_2}{L_1} = \frac{I_2}{I_1}\,\frac{V_F}{V_N}\,\frac{\Delta t_2}{\Delta t_1}\,e^{-\mu \Delta X}$$

$$\frac{R_1}{R_2} = \frac{I_1}{I_2}\,\frac{V_F}{V_N}\,\frac{\Delta t_1}{\Delta t_2}\,e^{-\mu \Delta X}$$

Multiply 2 equations and solve for μ → I_1, I_2, Δt_1, Δt_2 disappear

$$N_{SAT}(E_s) = \mu(E_s) = \frac{1}{2\Delta X}\,Ln\left[\frac{L_1}{L_2}\,\frac{R_2}{R_1}\right] - C$$

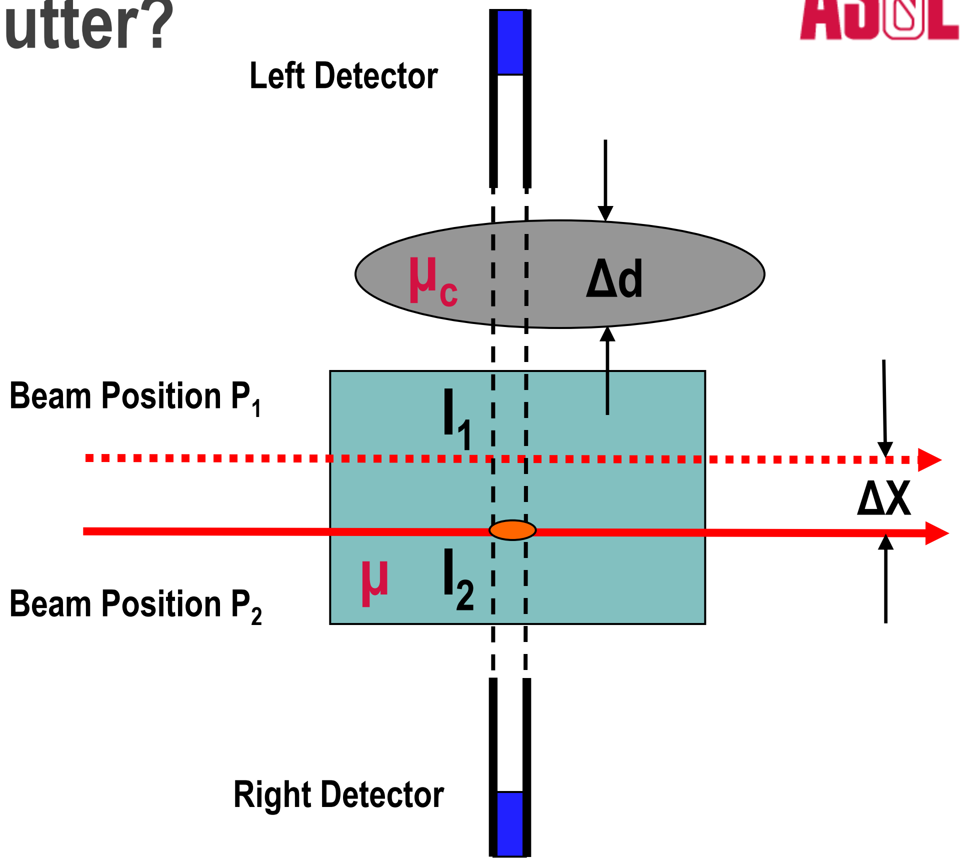
where $C = \frac{Ln\left(\frac{V_N}{V_F}\right)}{\Delta X} \sim 0$ (C can be calculated exactly from geometry, but is just an offset)

→ $$N_{SAT}(E_s) = \mu(E_s) = \frac{1}{2\Delta X}\,Ln\left[\frac{L_1}{L_2}\,\frac{R_2}{R_1}\right]$$

(Scatter Equivalent of the CT Number)

What about surrounding clutter?

Scattered radiation from the two voxels follows exactly the same path through the surrounding clutter, so the attenuation terms from near and far voxels cancel in the ratios



ρ_e = Electron Density
V_N, V_F = Voxel Volumes
Δt_1, Δt_2 = Integration Times

$$\frac{L_2}{L_1} = \frac{I_2}{I_1}\,\frac{\rho_e V_F}{\rho_e V_N}\,\frac{\Delta t_2}{\Delta t_1}\,\frac{e^{-\mu_c \Delta d}}{e^{-\mu_c \Delta d}}\,e^{-\mu \Delta X}$$

$$\frac{R_1}{R_2} = \frac{I_1}{I_2}\,\frac{\rho_e V_F}{\rho_e V_N}\,\frac{\Delta t_1}{\Delta t_2}\,e^{-\mu \Delta X}$$

$$\mu(E_s) = \frac{1}{2\Delta X}\,Ln\left[\frac{L_1}{L_2}\,\frac{R_2}{R_1}\right]$$

SAT Number (Scatter Analog of CT Number)

$$N_{SAT}(E_s) = \mu(E_s) = \frac{1}{2\Delta X} Ln\left[\frac{L_1}{L_2}\frac{R_2}{R_1}\right]$$

- N_{SAT} **depends only on *measurable* values** L_1, L_2, R_1, R_2
- **Does not require precise dwell times of beams (integration times all cancel)**
- **Measurement of N_{SAT} is not affected by attenuation of the incident beam or the scattered beams**
  - Not sensitive to surrounding "clutter"
- **Using a pair of energy-discriminating detectors and a polychromatic Bremstrahlung x-ray source allows N_{SAT} to be measured at multiple energies**
  - Yields independent measurements of density (ρ) and effective atomic number (Z_{eff})
  - Value of N_{SAT} is immune to beam hardening if the width of the energy bins is kept small
  - Beam hardening can be compensated for by measuring the mean energy of the scatter in a given energy bin and applying a correction factor

HOW CAN WE USE SAT?

AS&E
Detect the difference.

2010: 50kV SAT Bottled Liquid Scanner (BLS)

AS&E

Sample Chamber

Red/Green Light Notification

Single Touch-Button Operation

<u>2012:</u> 70kV SAT Bottled Liquid Scanner (BLS)

AS&E

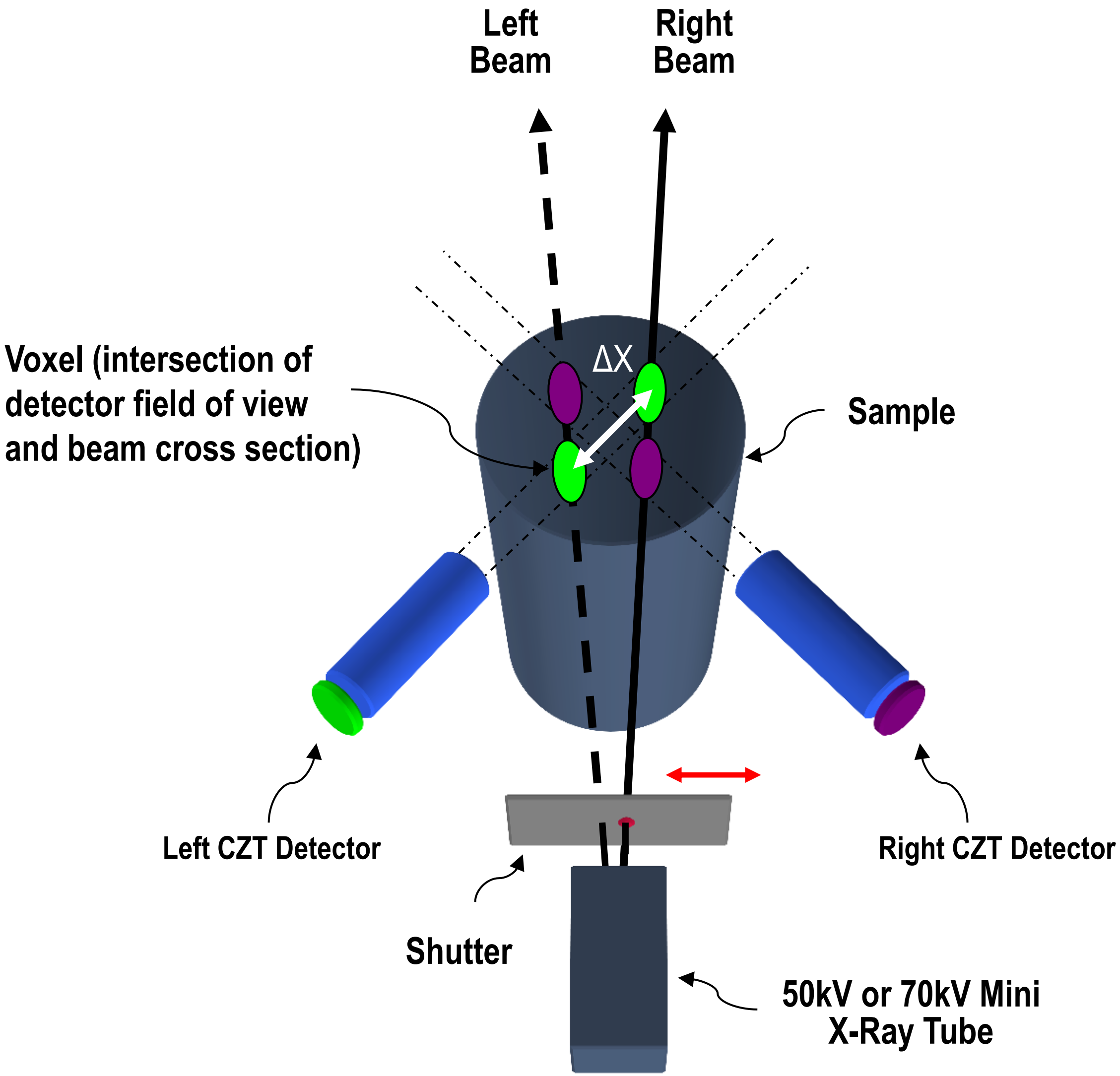
Sample Chamber
(automatic door)

Red/Green Light
Notification

Single Touch-Button
Operation

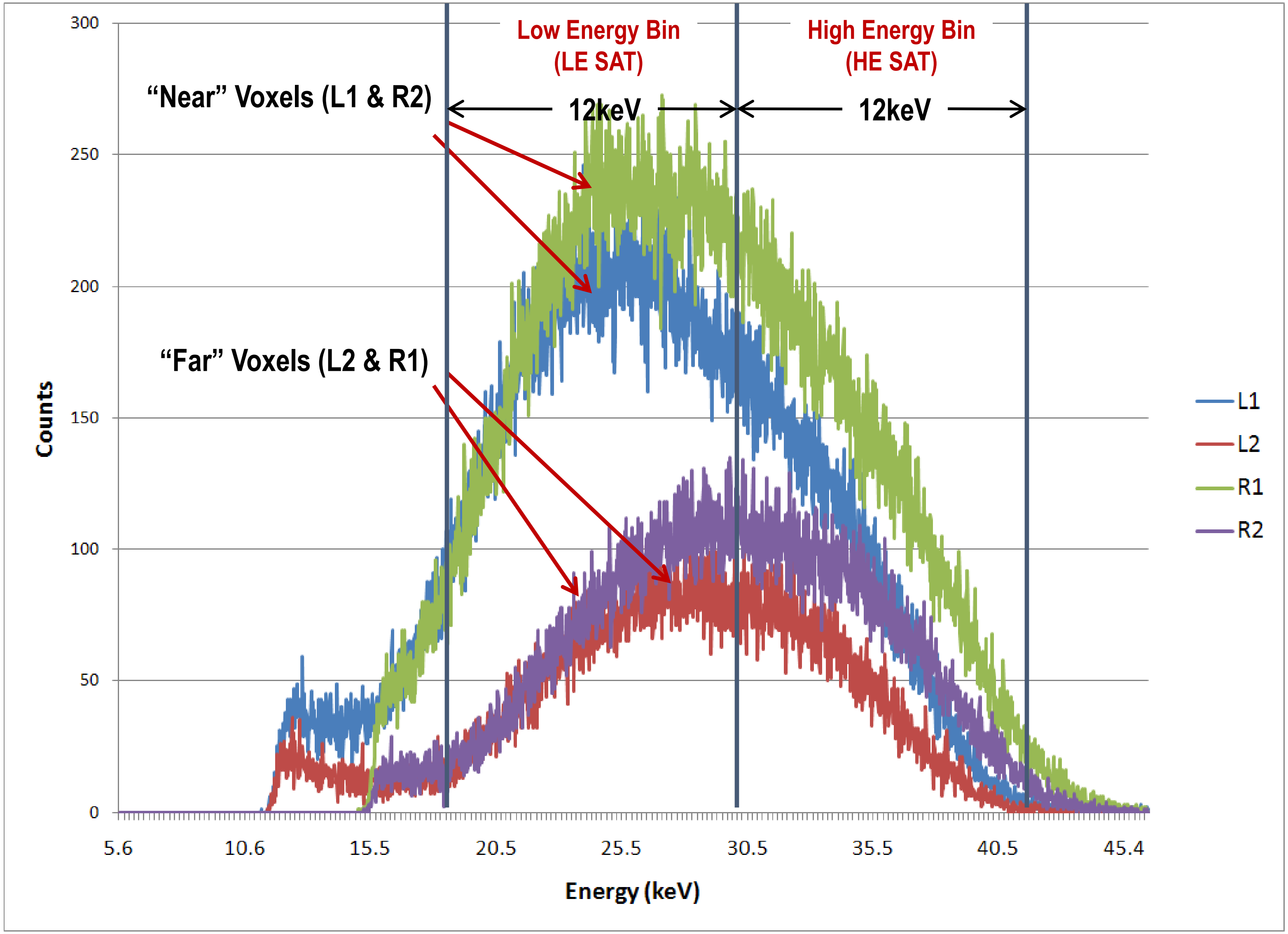
70kV allows much wider separation of low and high energy bins
→ improved ρ and Z_{eff} determination

SAT Tabletop BLS Geometry



Spectra Acquired on 50kV BLS System

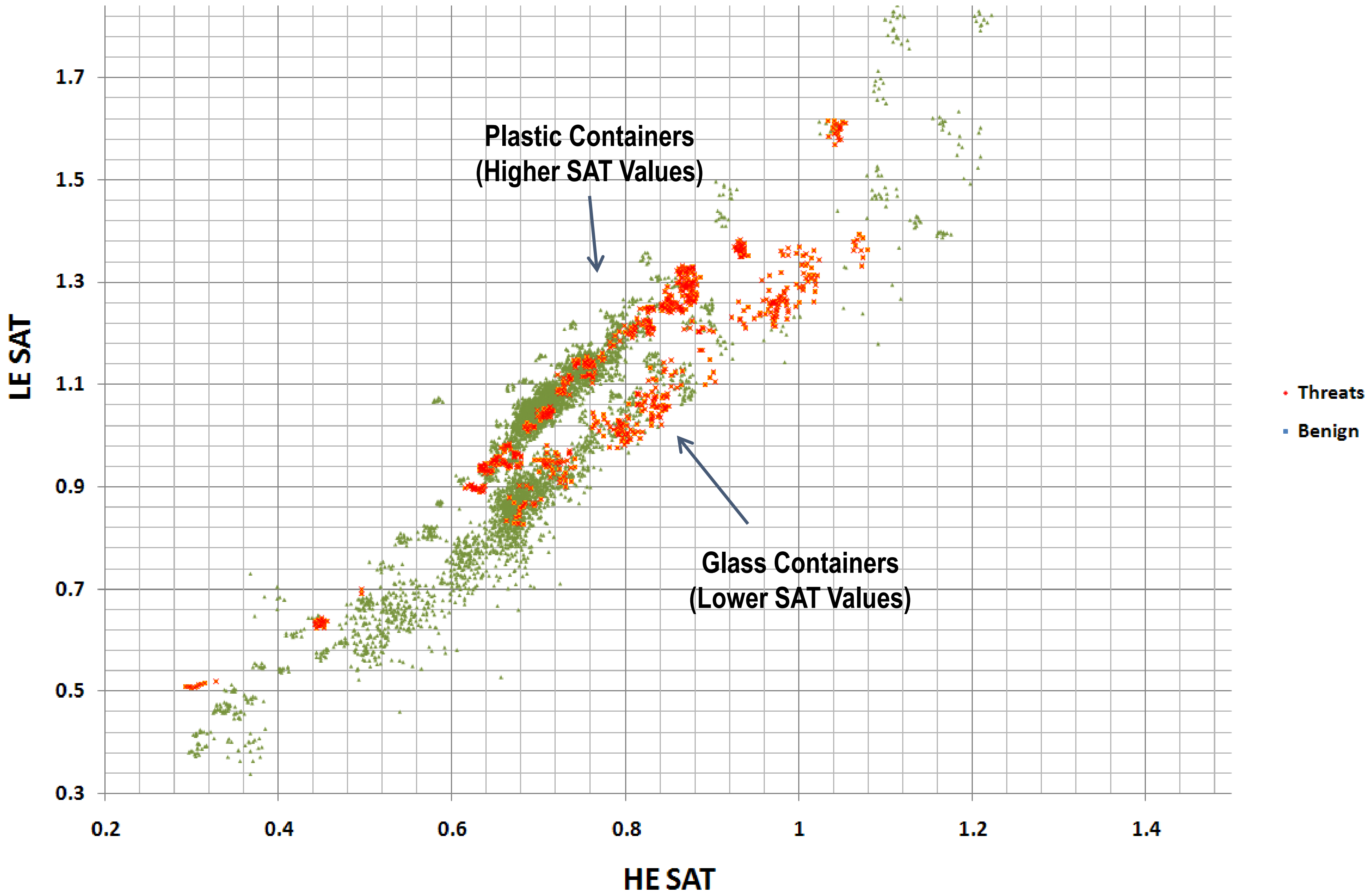
AS&E



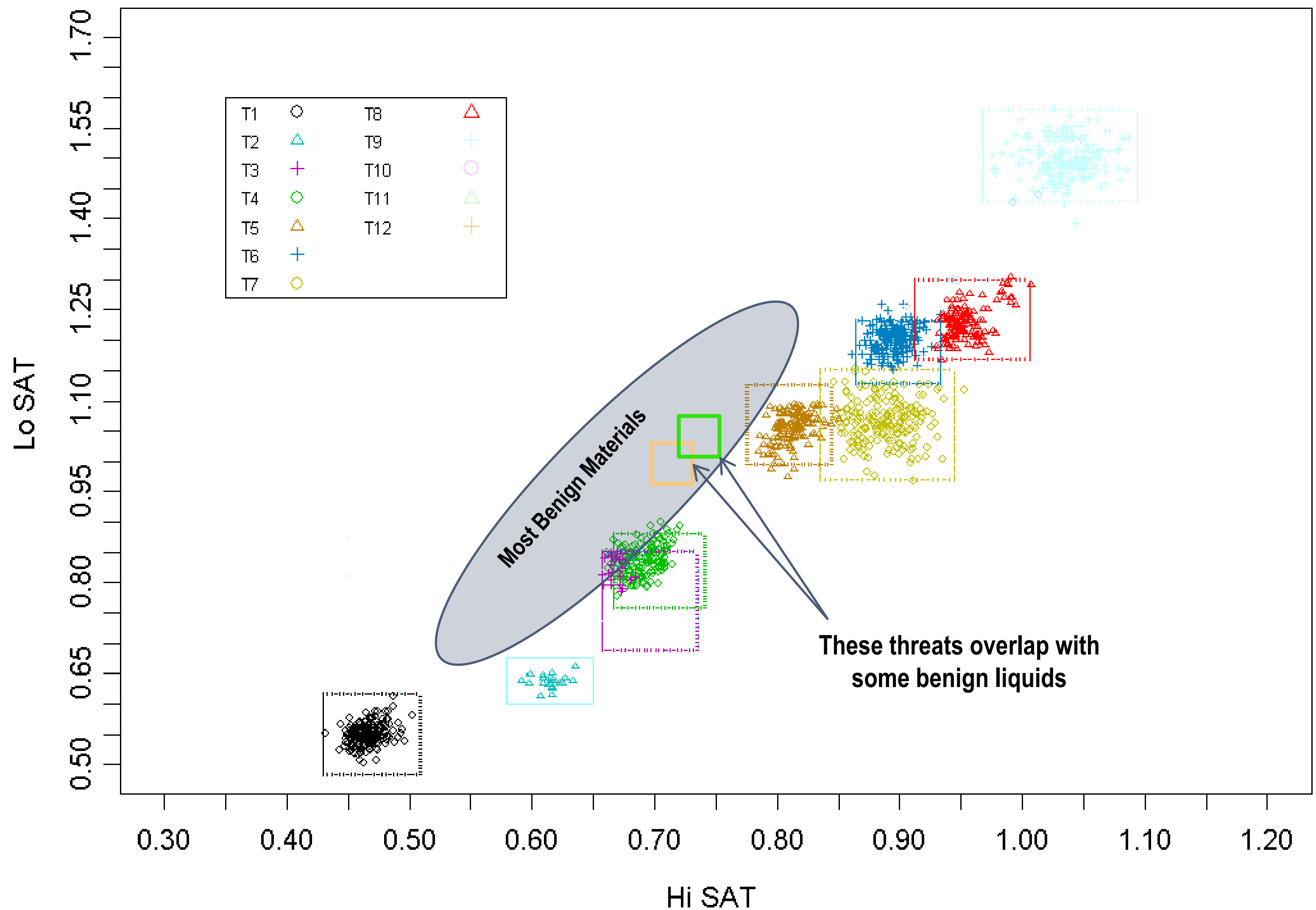
System Affected by Beam Hardening

- **Energy bins are fairly wide on the 50kV BLS system due to low power x-ray source (ΔE ~ 12keV)**
- **This means that the mean energy of the scattered x-rays in each bin can vary with container type, changing the measured SAT Numbers**
  - Use a classifier algorithm that compensates for this
  - Can use measured count rate or the mean energy in each bin to determine the container type
  - Use five separate classifiers for each major container category
    - e.g. thin plastic, thick plastic, thin glass, medium glass, thick glass

50kV Experimental SAT Data for Wide Range of Threat Liquids



Experimental SAT Data for Some Specific Liquid Threats

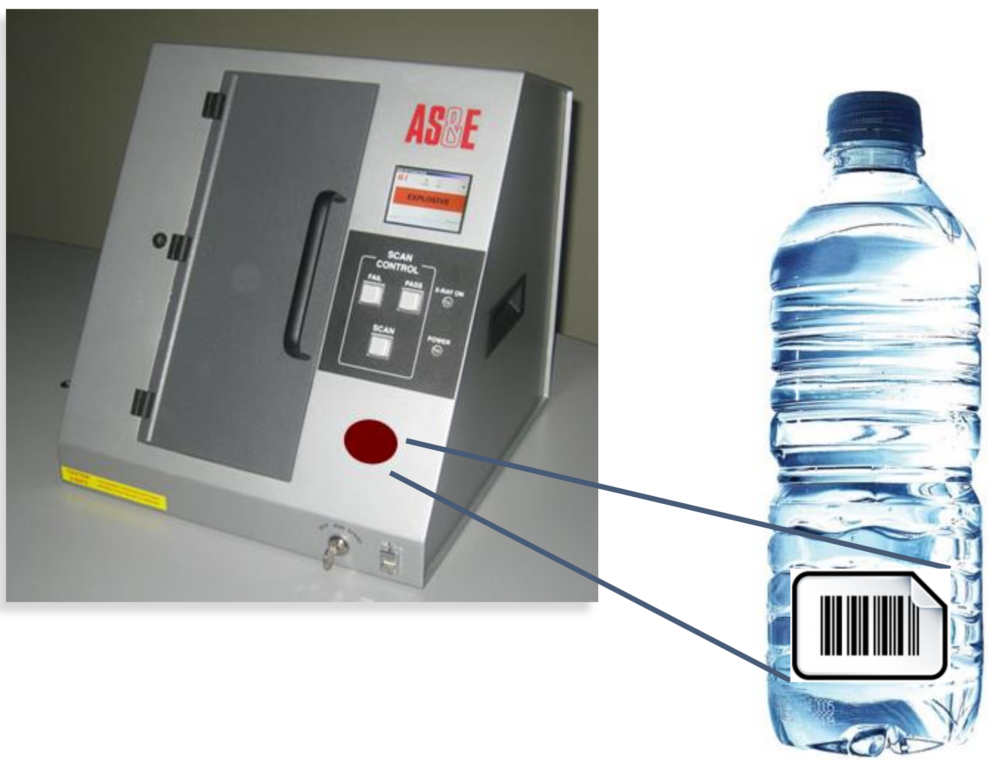


ONE SOLUTION IS A VALIDATION SYSTEM THAT USES A BARCODE SCANNER

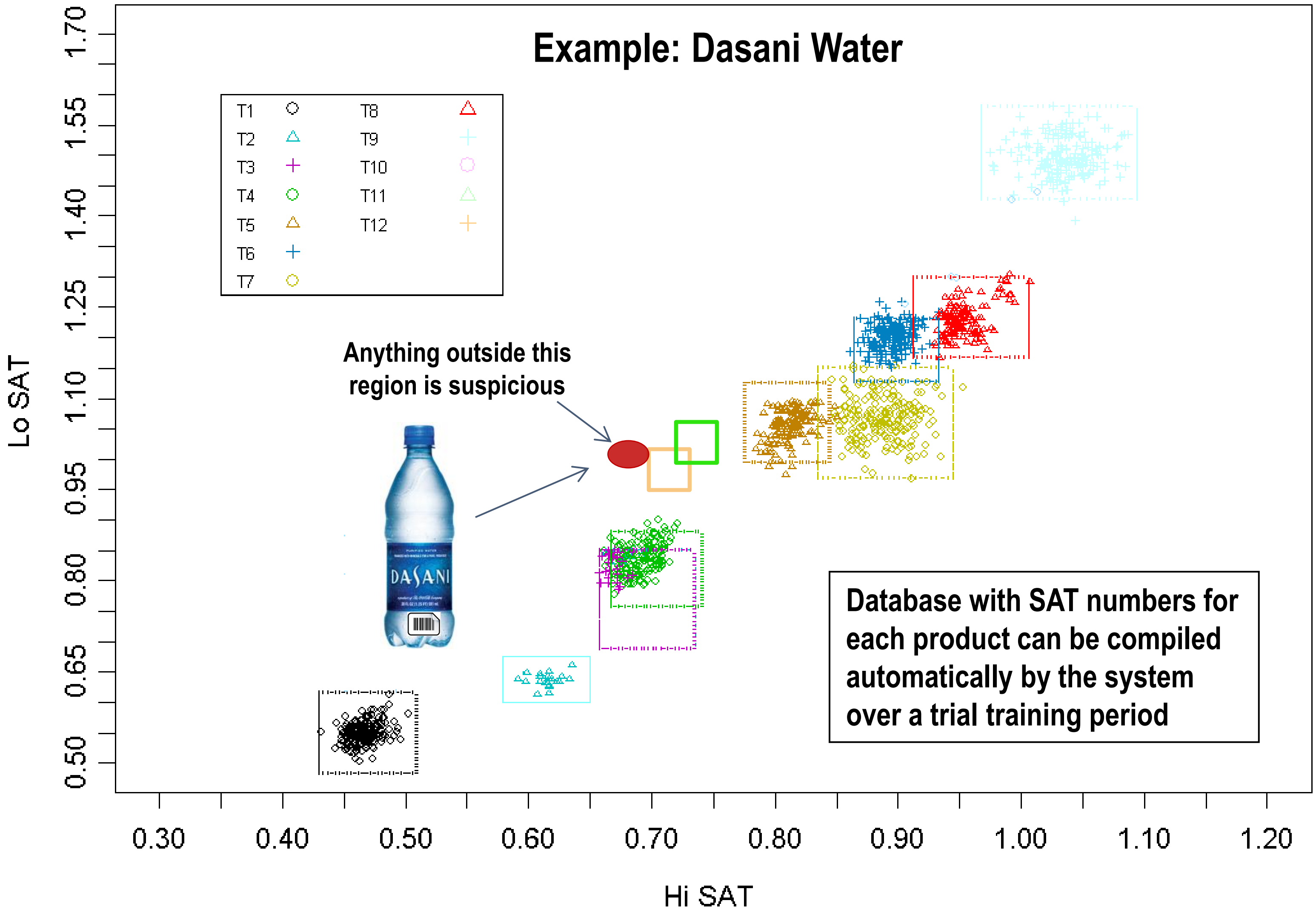
AS&E®
Detect the **difference.**

Barcode is scanned as bottle is placed inside system

System simply confirms that the SAT Numbers are what you would expect for the item being inspected



Barcode Identifies Exact Item and “Validates” It



Next Steps for SAT BLS

AS&E®

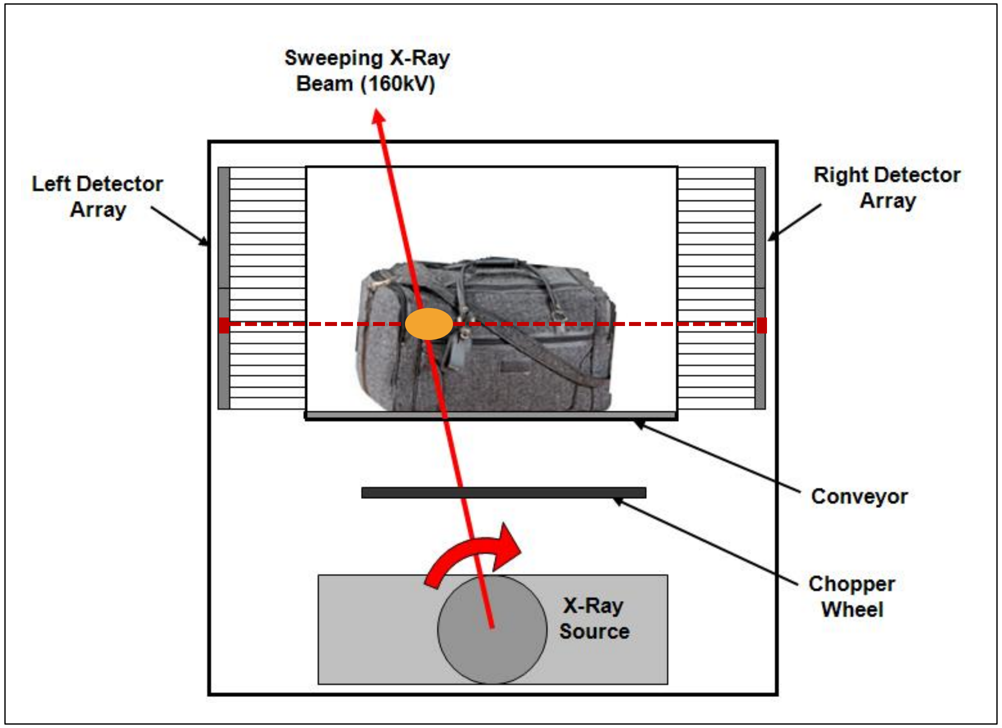
- **The 50kV SAT Tabletop system underwent testing for ECAC certification in Germany at Fraunhofer (Europe's largest application-oriented research organization)**
  - 50kV system achieved Category B Standard 1 certification
  - 10 seconds/bottle (plastic) and 20 seconds bottle (thick glass)
- **System was upgraded from 50kV to 70kV to attempt Standard 2 certification**
  - Greatly decreased scan times (2-5 sec/bottle)
  - Approximately 1 second / bottle for a validation system with a barcode scanner
  - 70kV system has not been sent for ECAC certification testing (decision by AS&E not to pursue liquid scanning)

SAT FOR BAGGAGE INSPECTION

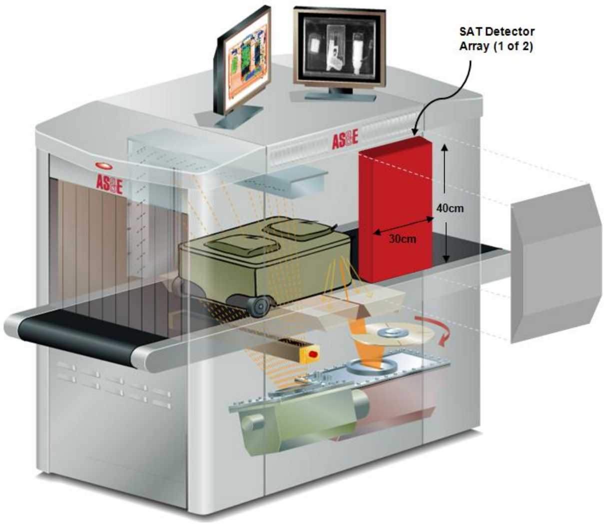
AS&E®
Detect the **difference.**

Concept for 100% Inspection of Baggage

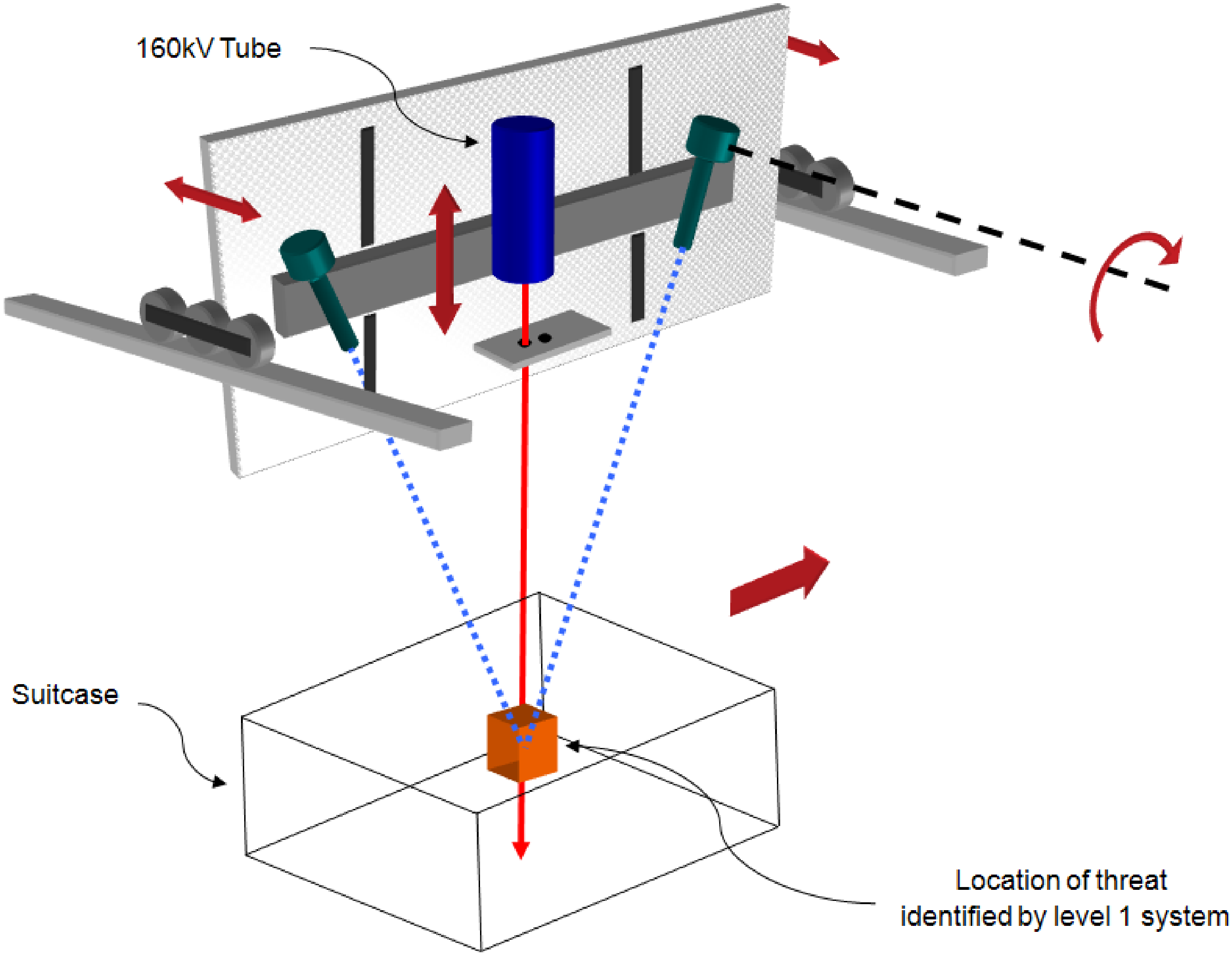
- In principle, a sweeping x-ray beam and two arrays of collimated scatter detectors can give 100% coverage of baggage.
- Each pair of detector elements analyzes a horizontal slice of the bag
- Detectors collimated in only one dimension are vulnerable to multiple scatter which can affect the SAT Number measurement
- The beam intensity must be very high for realistic throughput rates (10's of kWs)



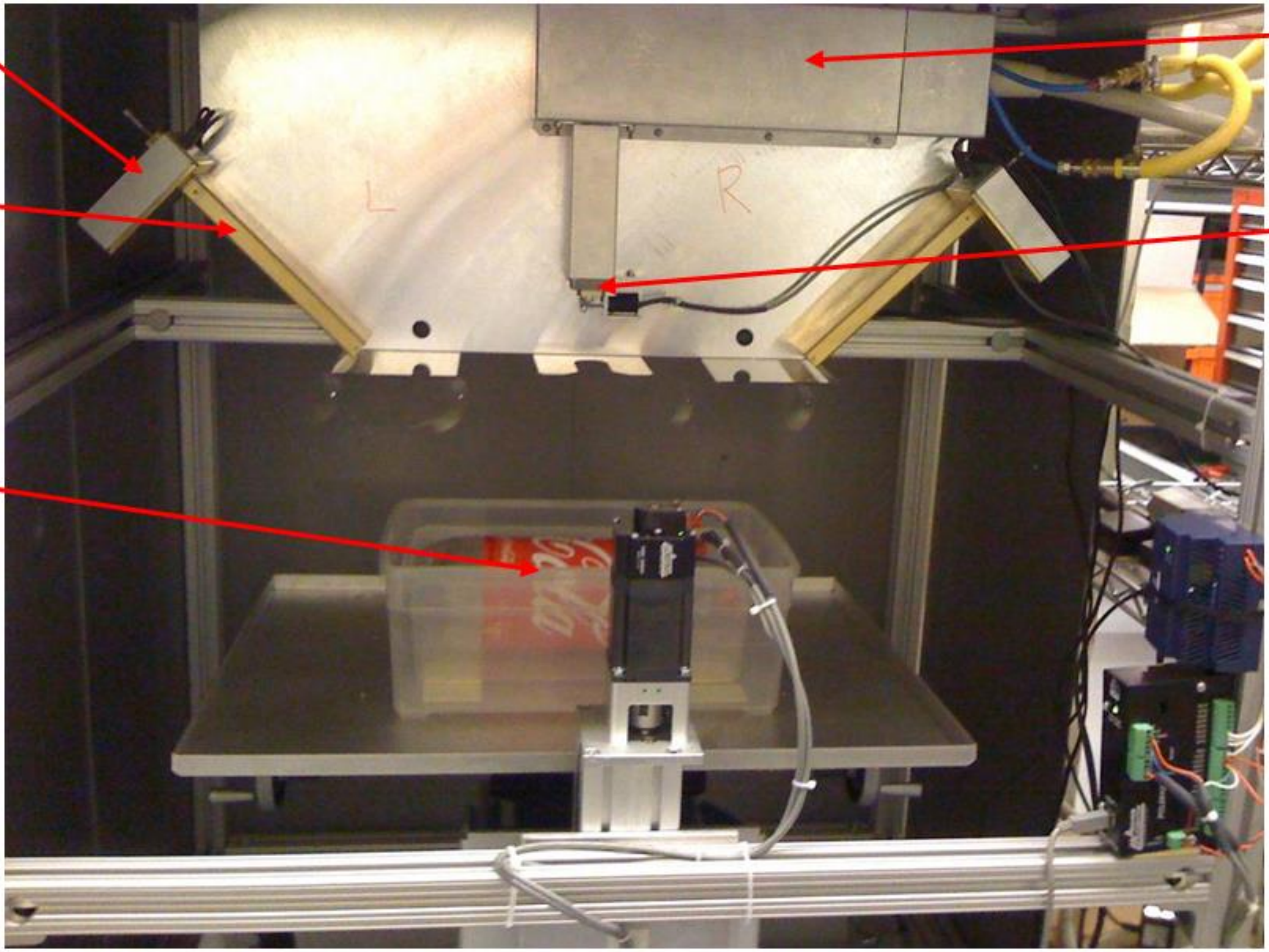
AS&E Gemini ™ System (Contains a Sweeping 160kV Beam)



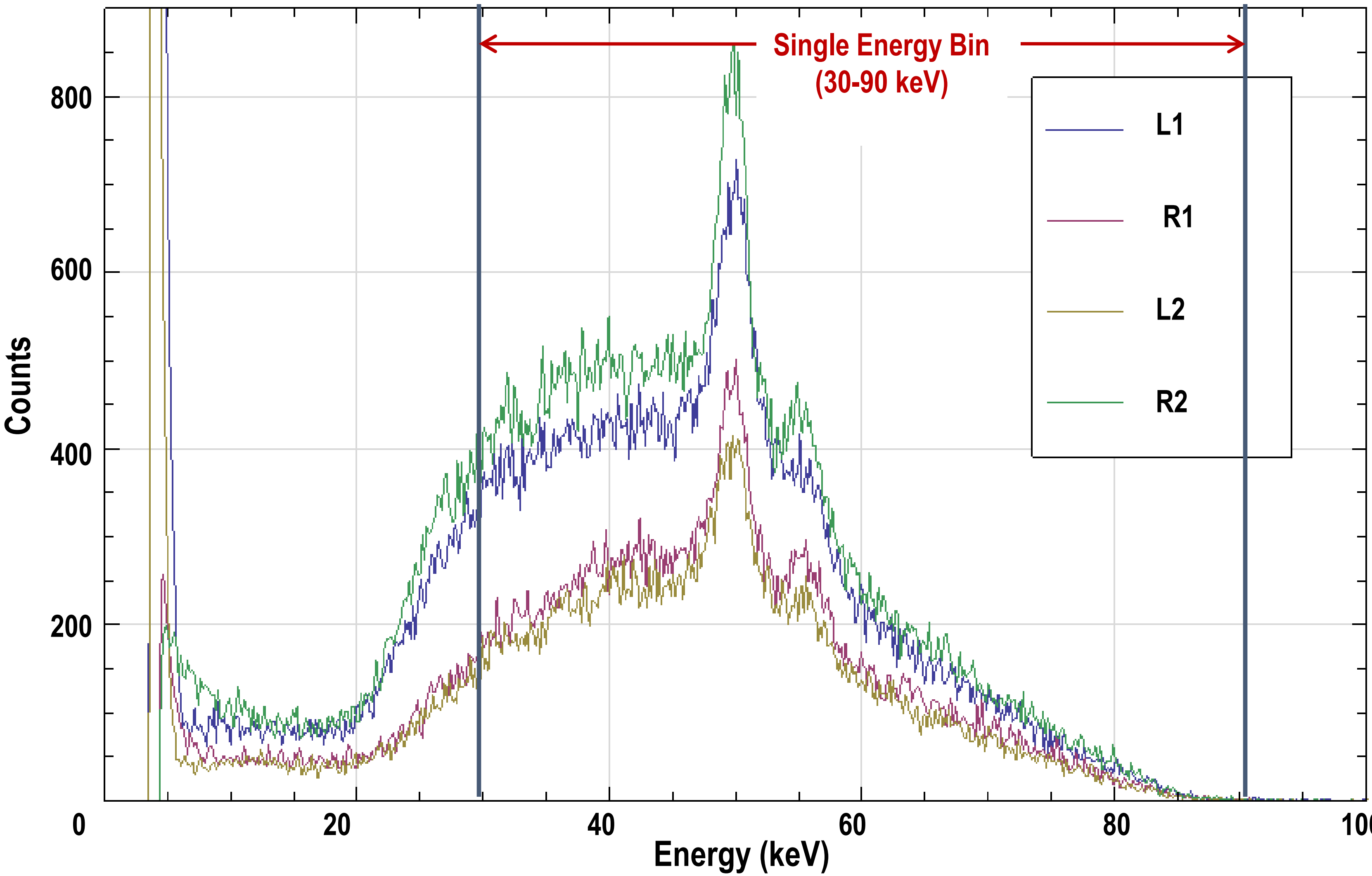
Concept for Level-2 Inspection of Baggage



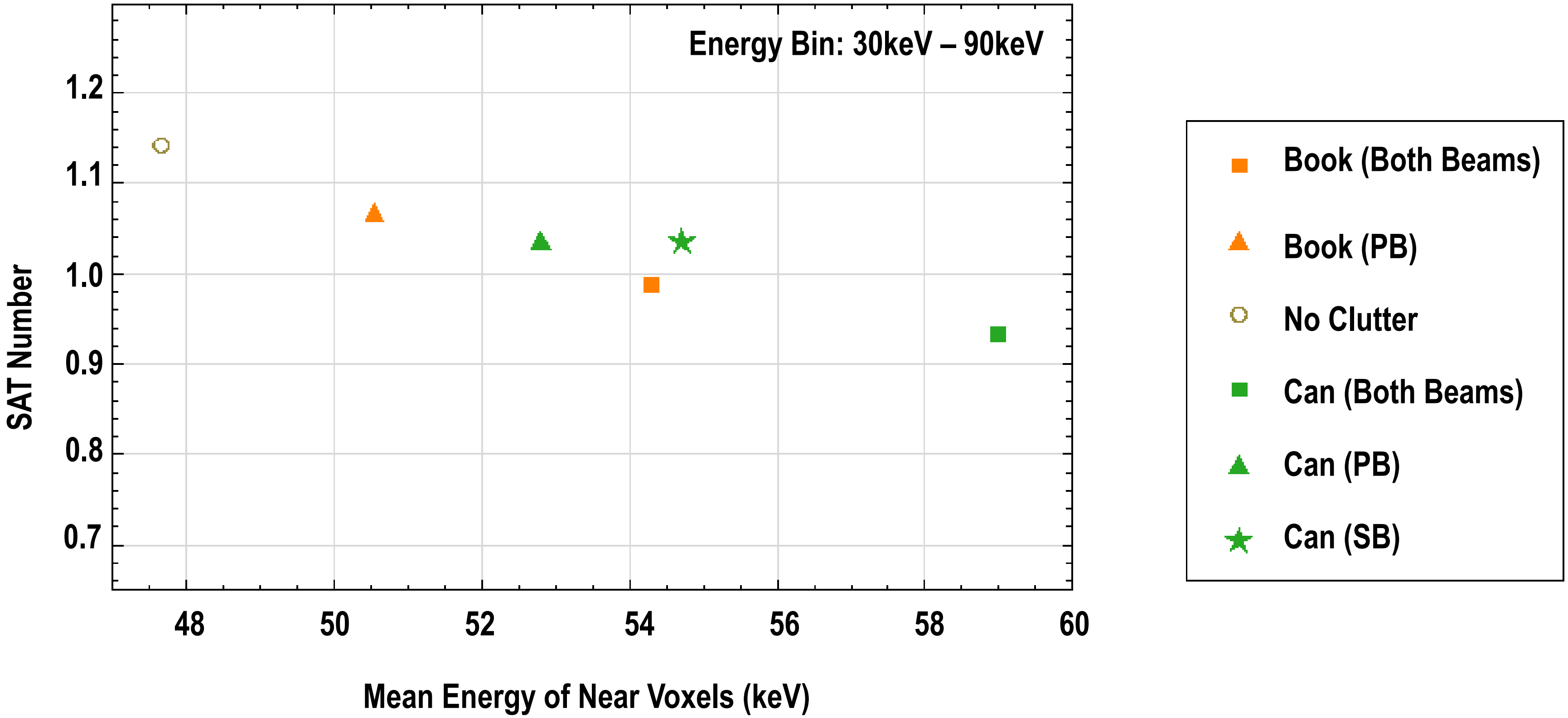
120kV Laboratory Test Stand



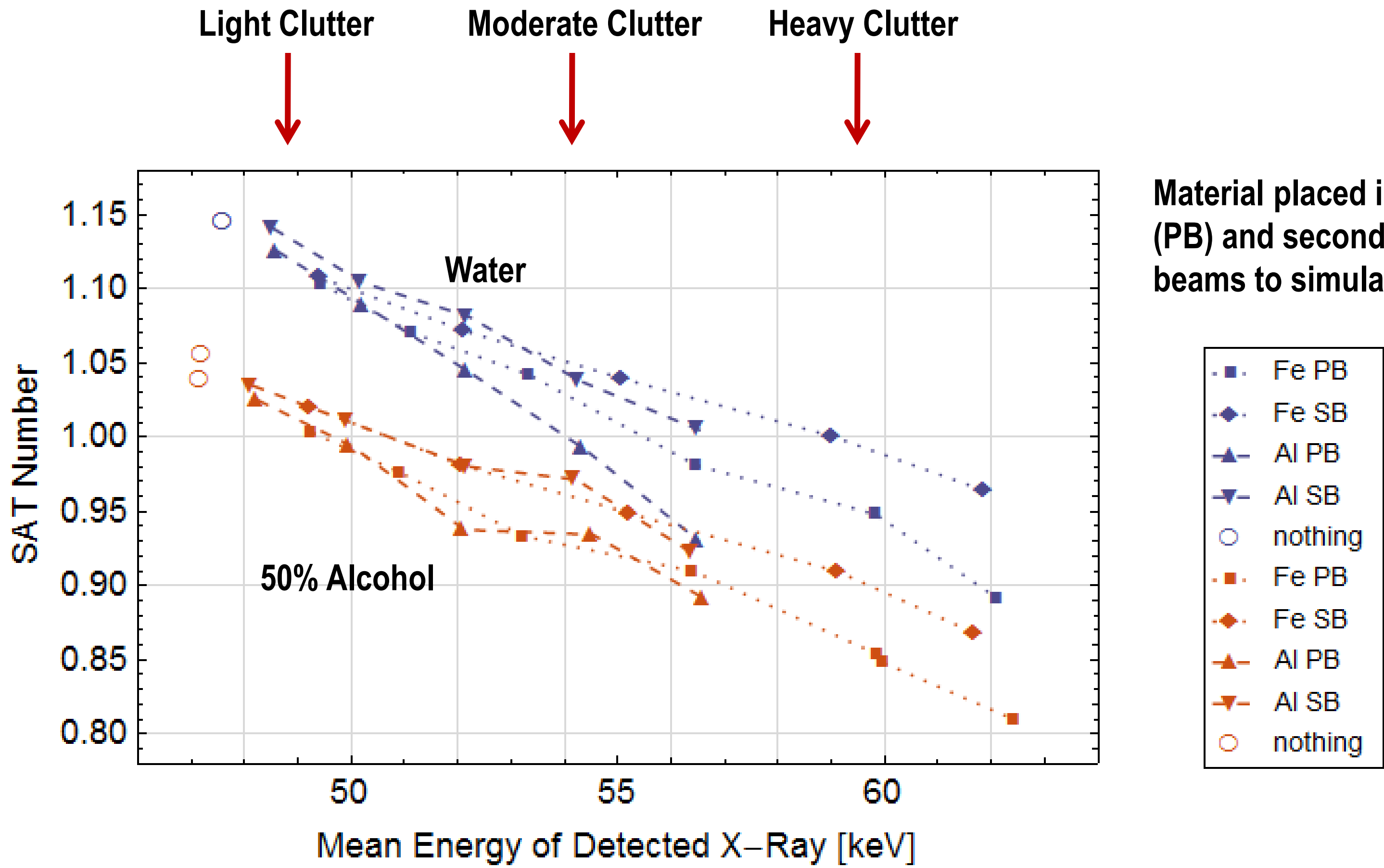
Spectra Acquired with 120kV Test Stand



Effect of Beam Hardening for water with 120kV System



Experimental Results at 120kV for Liquid Identification



Material placed in primary (PB) and secondary (SB) beams to simulate clutter

SAT FOR CARGO INSPECTION

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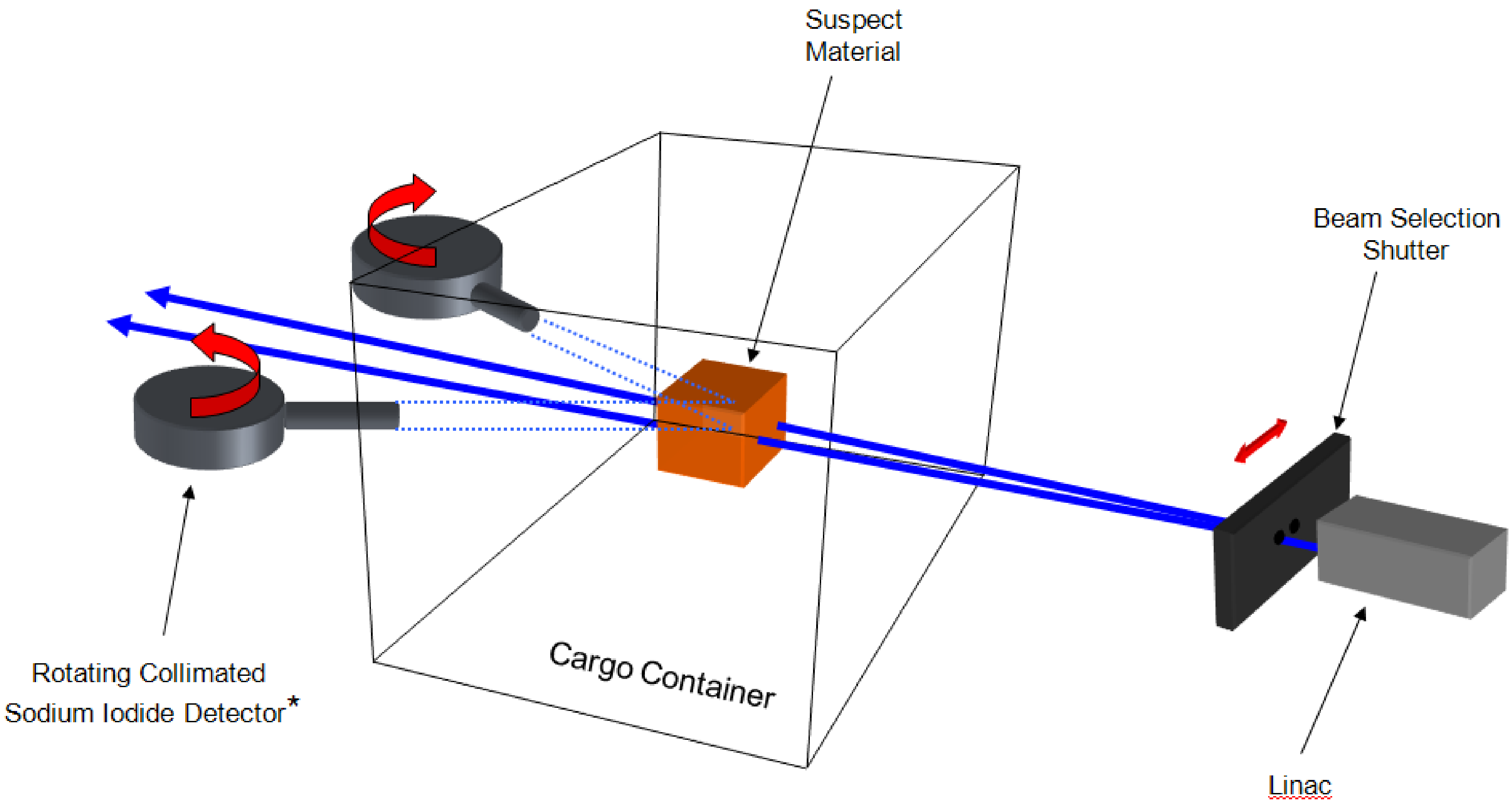
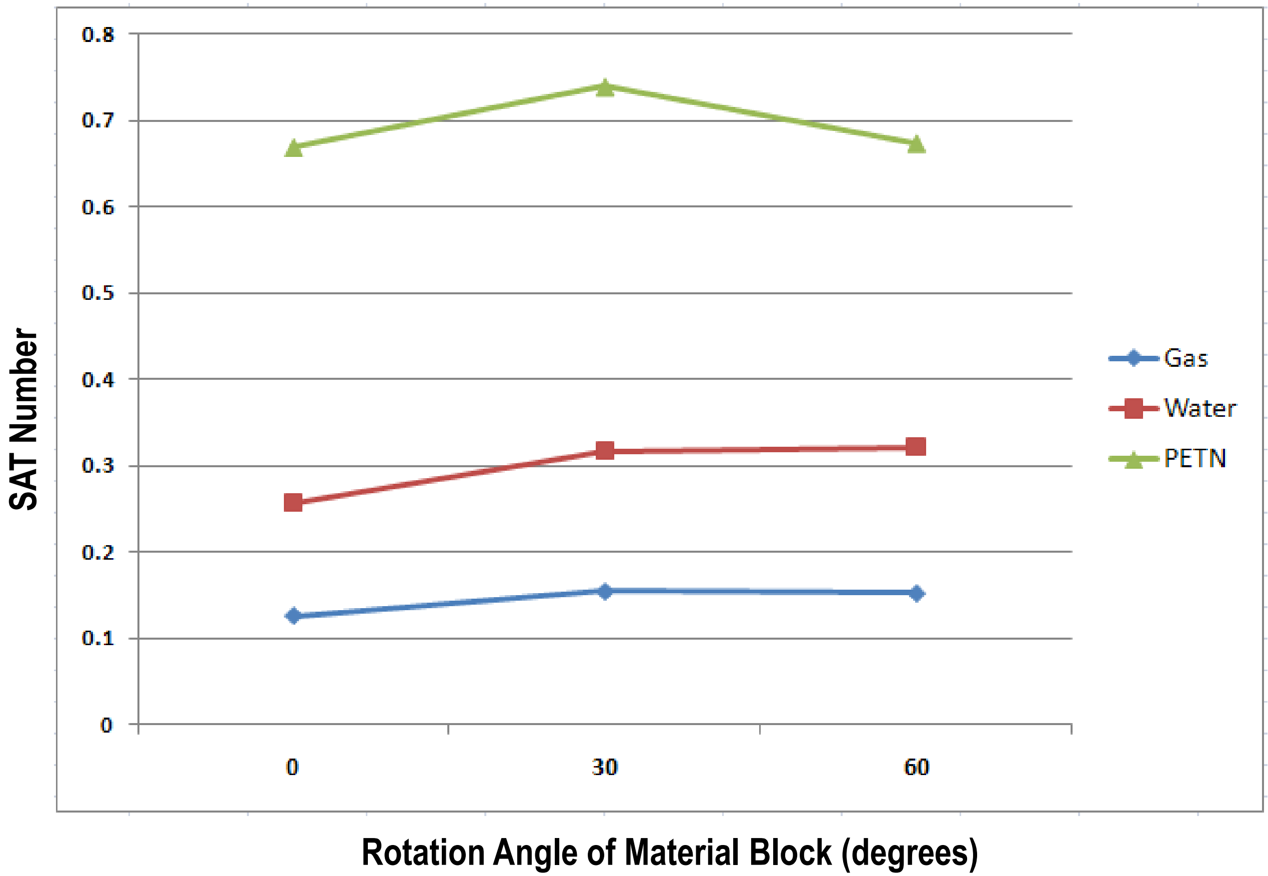
Detect the **difference.**

Concept for Level 2 Inspection of Cargo



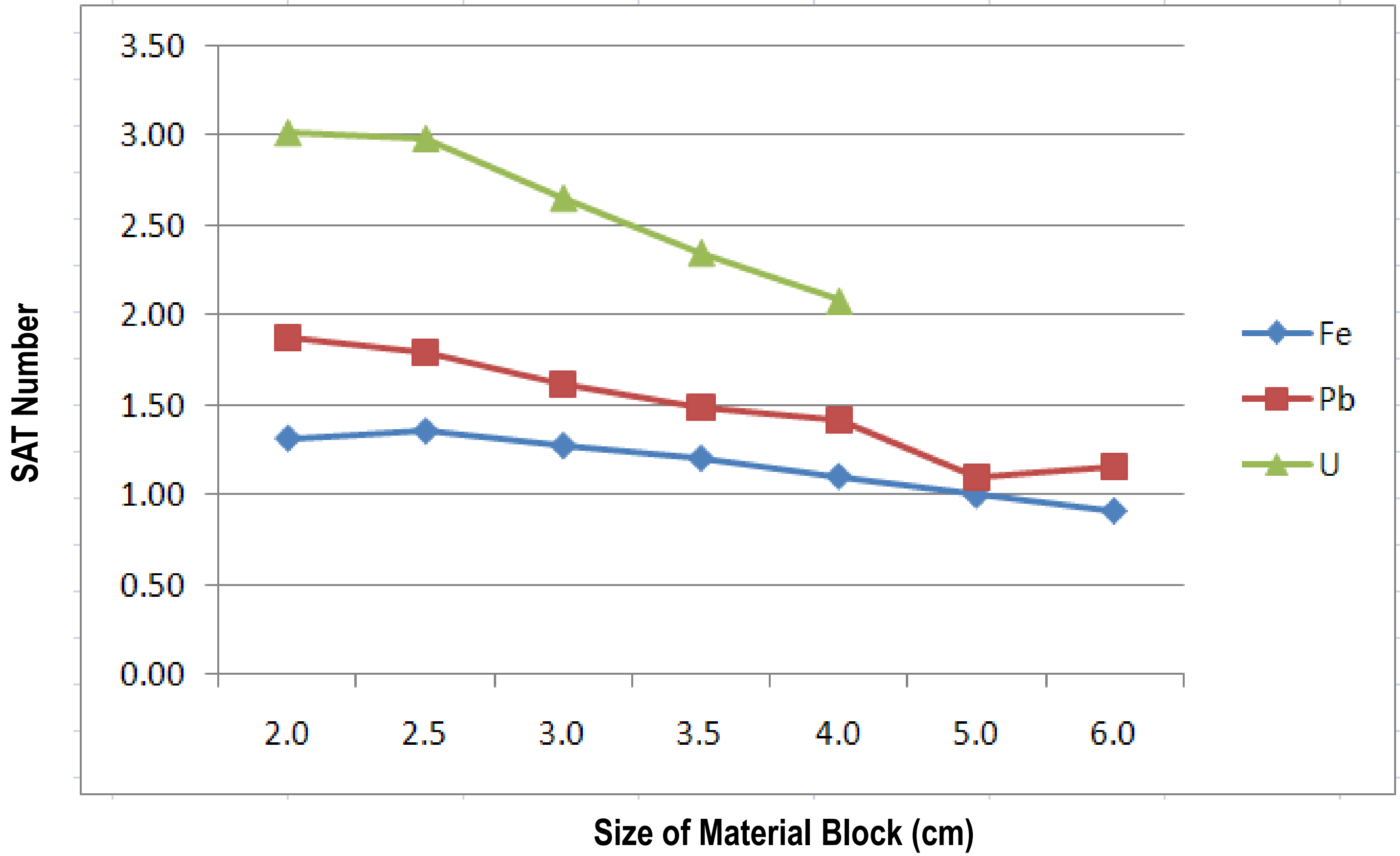
*Rotation Angle of detectors selects depth of object being interrogated

Simulation of Organic Material Identification in Cargo at 6MeV



Cubes of material placed in
36” crate of cotton cloth
6 MeV Bremstrahlung spectrum
2.8×10^{10} x-rays in each beam

Simulation of High-Z Material Identification in Cargo at 6MeV



Cubes of material placed in
36" crate of cotton cloth
6 MeV Bremstrahlung spectrum
2.8x10^{10} x-rays in each beam

Conclusions

- SAT is a promising new x-ray technique for identifying materials
  - Very robust to surrounding clutter
  - Highly specific (sensitive to both density and atomic number)
  - Beam hardening effects can be easily corrected for
- SAT is a point interrogation method better suited to level 2 inspection
  - Acquisition times are typically on the order of 1-10 seconds per interrogation
  - Level 1 screening applications would require fairly intense x-ray sources
- We believe that there are many potential applications for this technology
  - Non-Destructive Testing (NDT)
    - Material characterization, void detection
  - Counterfeit pharmaceutical detection
- Selected for funding under DHS BAA 13-05 (in collaboration with LLNL, Tufts, Multix)

THANK YOU

SAT WITH MONOCHROMATIC SOURCES

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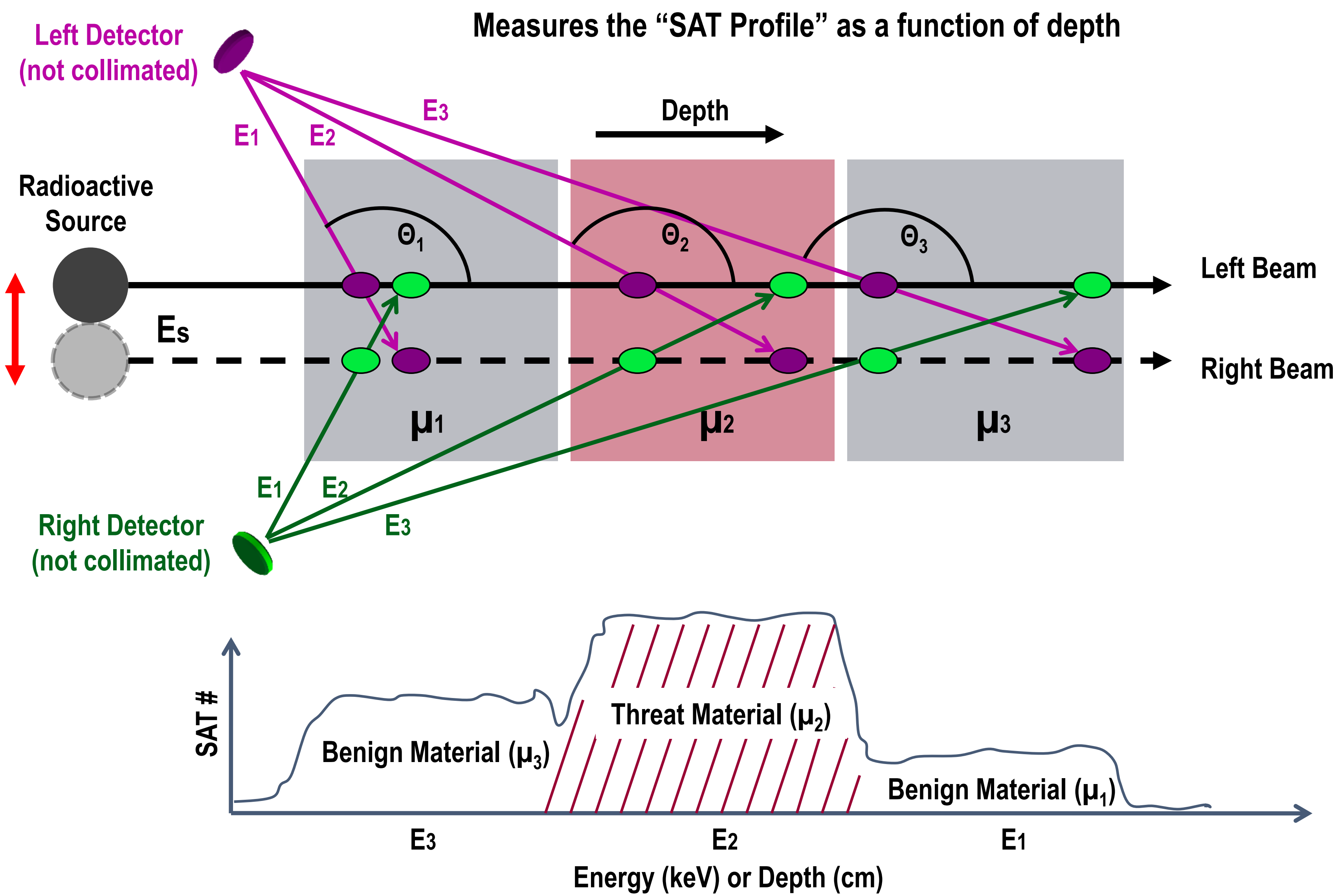
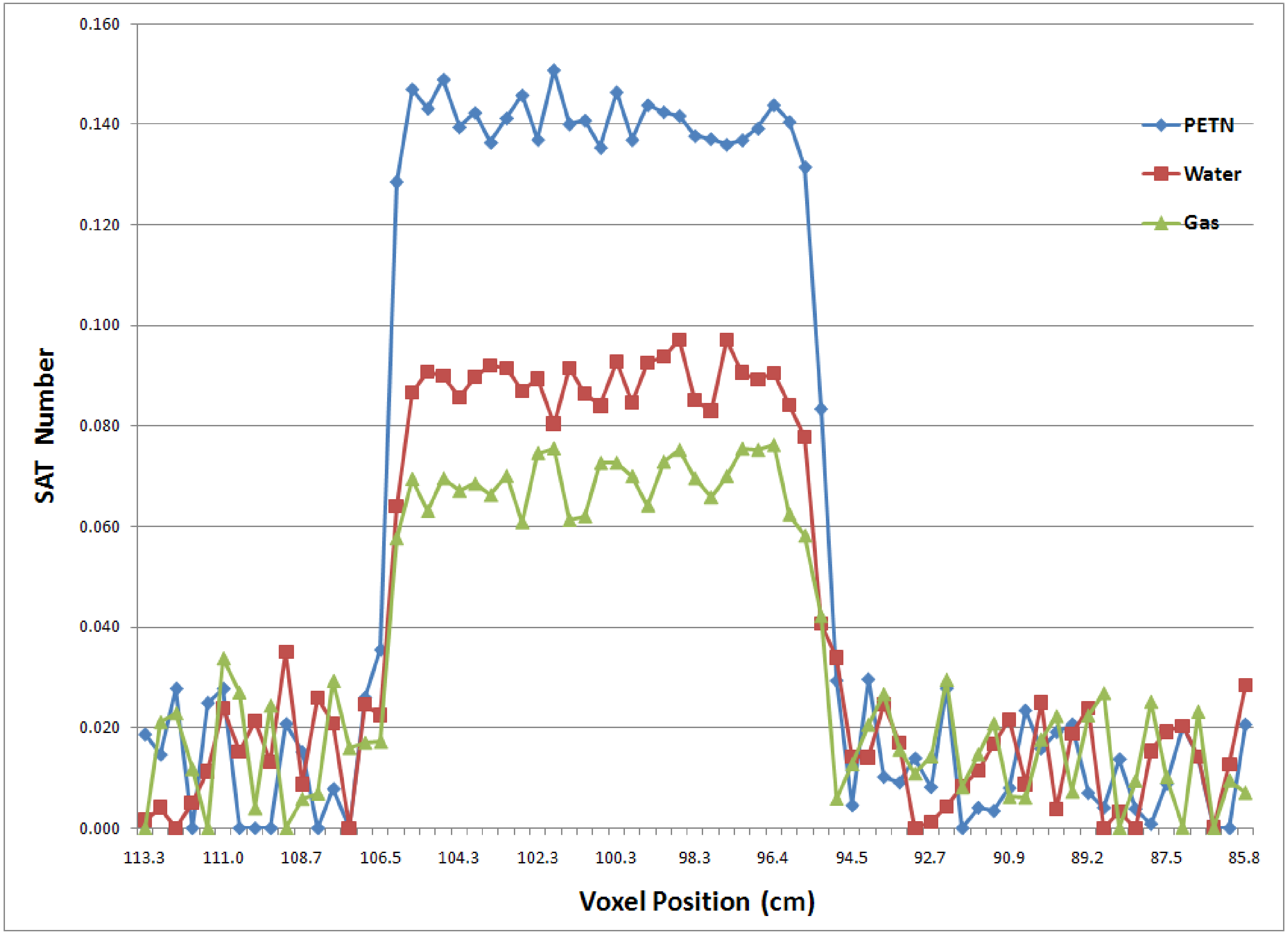
Detect the difference.

Concept for SAT with Radioactive Sources



Simulation Results (10cm Cube at Center of 1m Sphere of Cotton)



Future Developments

- **Investigate Use of SAT for Non-Destructive Testing Applications**
  - Material classification
    - Density Measurement
    - Effective Atomic Number Measurement
  - Void detection in Uniform Materials
  - Mining applications
    - Soil or rock classification
    - Metal content of ore
  - Counterfeit Pharmaceutical Detection
  - Quality Control

SAT Related Patents

Two Issued SAT Patents: AS&E (Rothschild)

June, 2009

US007551718B2

(12) **United States Patent**
Rothschild

(10) **Patent No.:** **US 7,551,718 B2**
(45) **Date of Patent:** **Jun. 23, 2009**

(54) **SCATTER ATTENUATION TOMOGRAPHY**

(75) Inventor: **Peter J. Rothschild**, Boston, MA (US)

(73) Assignee: **American Science and Engineering, Inc.**, Billerica, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 163 days.

(21) Appl. No.: **11/843,185**

(22) Filed: **Aug. 22, 2007**

(65) **Prior Publication Data**

US 2008/0049899 A1 Feb. 28, 2008

Related U.S. Application Data

(60) Provisional application No. 60/823,328, filed on Aug. 23, 2006.

(51) **Int. Cl.**
G01N 23/201 (2006.01)

(52) **U.S. Cl.** **378/88**; 378/89

(58) **Field of Classification Search** 378/86, 378/87, 88, 89

See application file for complete search history.

(56) **References Cited**

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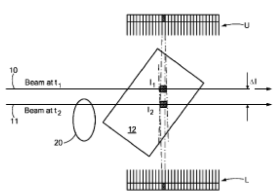
Primary Examiner—Chih-Cheng G Kao
(74) *Attorney, Agent, or Firm*—Bromberg & Sunstein LLP

(57) **ABSTRACT**

Methods for characterizing an inspected object on the basis of attenuation determined from pair-wise illuminated voxels. A beam of penetrating radiation characterized by a propagation direction and an energy distribution is scanned across an object, while scatter detectors with collimated fields-of-view detect radiation scattered by each voxel of the inspected object that is intercepted by the incident beam of penetrating radiation. By calculating the attenuation of penetrating radiation between pairs of voxels of incidence of the incident beam, a tomographic image is obtained characterizing the three-dimensional distribution of attenuation in the object of one or more energies of penetrating radiation, and thus of various material characteristics.

14 Claims, 7 Drawing Sheets



April, 2011

US007924979B2

(12) **United States Patent**
Rothschild

(10) **Patent No.:** **US 7,924,979 B2**
(45) **Date of Patent:** **Apr. 12, 2011**

(54) **SCATTER ATTENUATION TOMOGRAPHY**

(75) Inventor: **Peter J. Rothschild**, Newton, MA (US)

(73) Assignee: **American Science and Engineering, Inc.**, Billerica, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/551,972**

(22) Filed: **Sep. 1, 2009**

(65) **Prior Publication Data**

US 2010/0034347 A1 Feb. 11, 2010

Related U.S. Application Data

(63) Continuation-in-part of application No. 12/489,620, filed on Jun. 23, 2009, now abandoned, which is a continuation of application No. 11/843,185, filed on Aug. 22, 2007, now Pat. No. 7,551,718.

(60) Provisional application No. 60/823,328, filed on Aug. 23, 2006.

(51) **Int. Cl.**
G01N 23/201 (2006.01)

(52) **U.S. Cl.** **378/88**

(58) **Field of Classification Search** 378/86, 378/87, 88, 89

See application file for complete search history.

(56) **References Cited**

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4,144,457	A	3/1979	Albert	250/445
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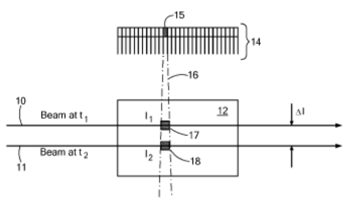
(57) **ABSTRACT**

A system and methods for characterizing an inspected object on the basis of attenuation determined from pair-wise illuminated voxels. A beam of penetrating radiation characterized by a propagation direction and an energy distribution is scanned relative to an object, while scatter detectors with collimated fields-of-view detect radiation scattered by each voxel of the inspected object that is intercepted by the incident beam of penetrating radiation. By calculating the attenuation of penetrating radiation between pairs of voxels illuminated sequentially by the incident beam, a tomographic image is obtained characterizing the three-dimensional distribution of attenuation in the object of one or more energies of penetrating radiation, and thus of various material characteristics.

20 Claims, 14 Drawing Sheets



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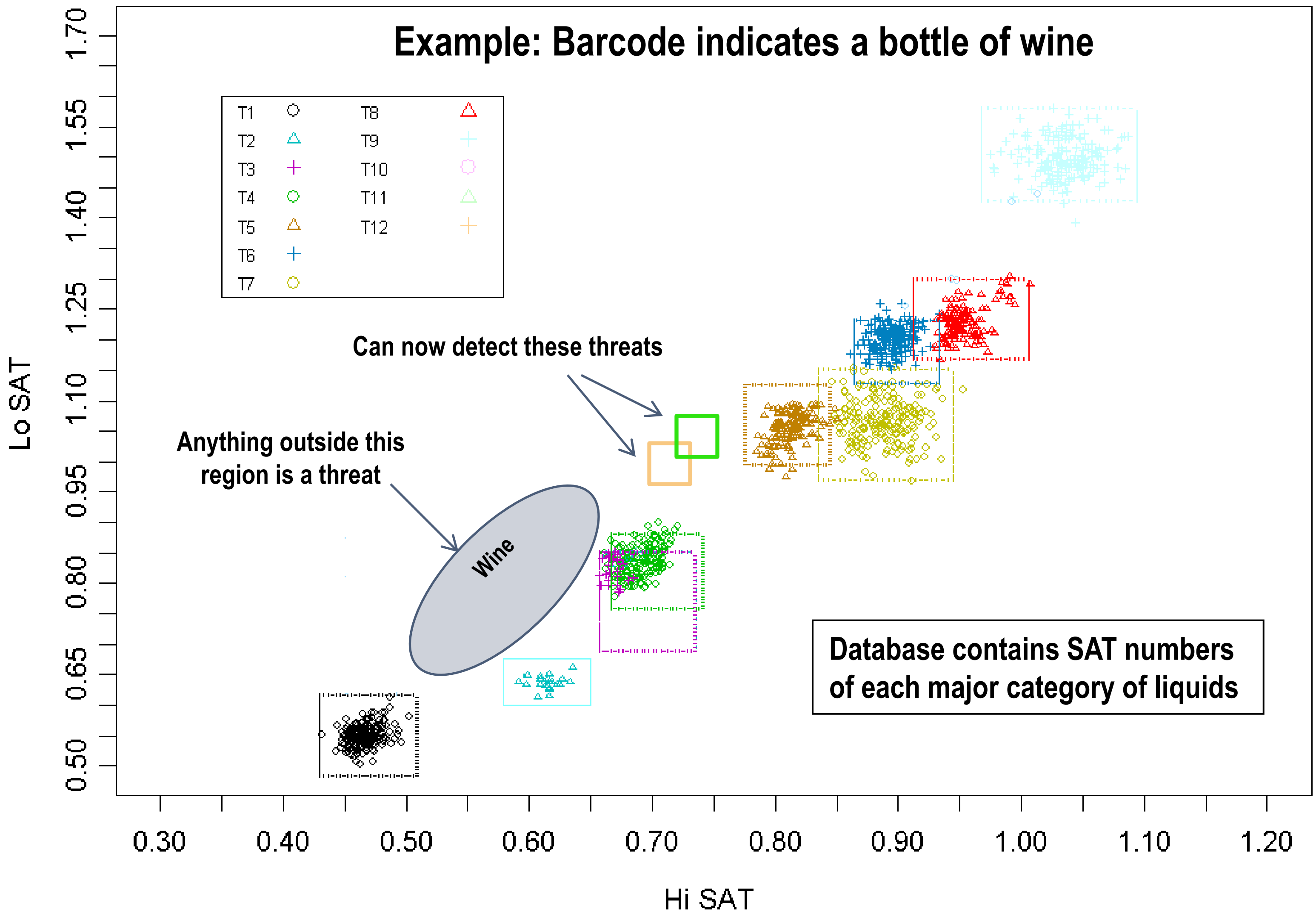

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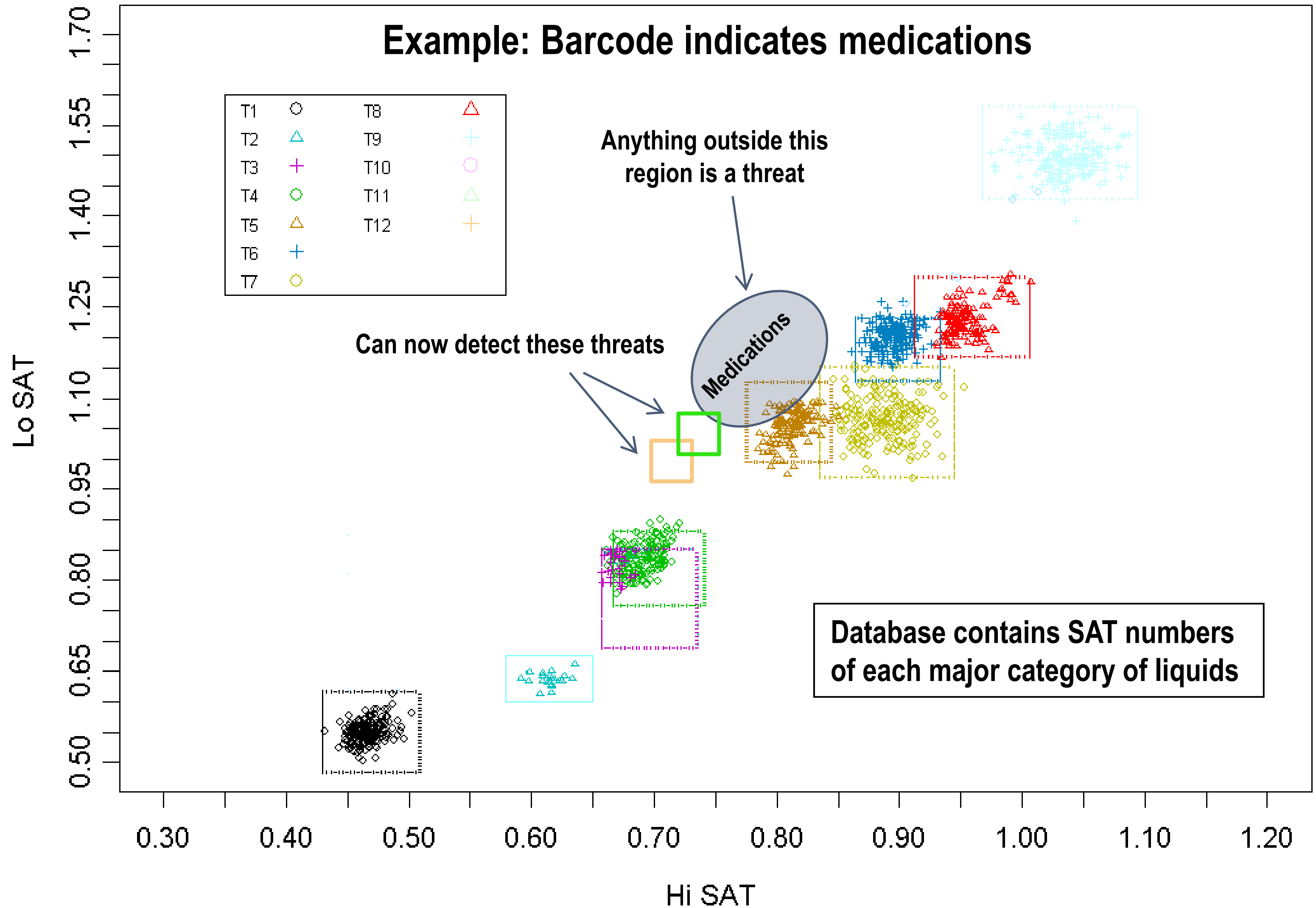

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