LLNL-PRES-731203

Dual-Energy Decomposition Methods for Accurate Material Discrimination

ADSA 16

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May 3, 2017

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Nondestructive Characterization Institute

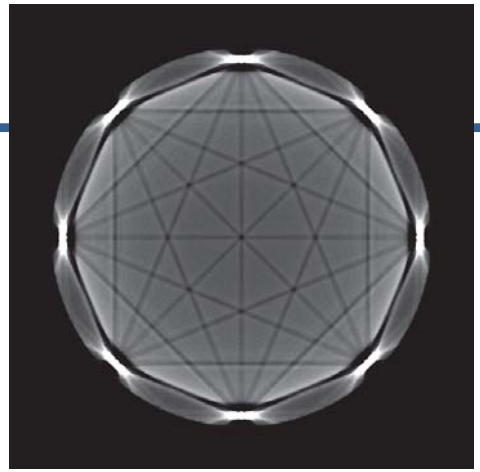
LEDP Livermore Explosives Detection Program

LLNL-PRES-731203

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

(ρ_e, Z_e) is useful for precise and accurate material discrimination

Single-Energy:
Artifacts hide features



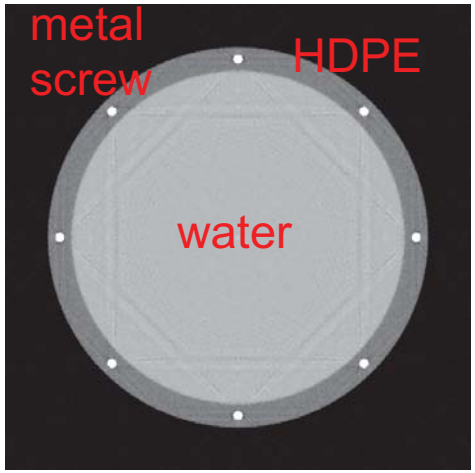
Physical properties provide a system independent feature space.

Different dual-energy decomposition methods available.

Propose an adaptive method for a system-to-system transfer function.

Reduced artifacts and errors over entire material range may lead to increased P_D and lowered P_{FA}.

Dual-Energy:
Reduces artifacts



Absolute relative error of LAC estimate at 44 keV

Basis Type	HDPE (Z_e=5.4)	Water (Z_e=7.45)	Al (Z_e=13)	Brominated Delrin (Z_e=17.0)
LAC (PCD)	0.10 %	0.18 %	0.03 %	3.28%
Adaptive	0.16 %	0.14 %	0.10 %	0.17 %

Approximate Multi-Spectral CT Model

Multi-spectral decomposition approximates energy- and spatial- dependent linear attenuation coefficients (LAC) with a separable basis expansion:

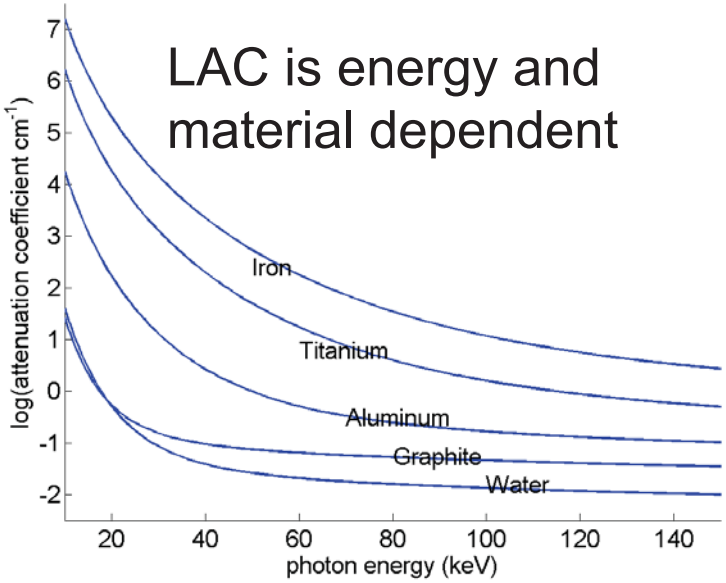
$$\mu(E,x) \approx \sum_i b_i(E)c_i(x)$$

x-ray energy

spatial location

basis function

basis coefficient



Effectiveness of multi-spectral decomposition depends on the accuracy of the above basis expansion

Pros and Cons of Two Common Bases

Alvarez and Macovski, Phys. Med. Biol., 1976
Ying, Naidu, & Crawford, J. X-ray Sci. and Tech., 2006
Azevedo et al., IEEE Trans. Nucl. Sci., 2016

Compton/ photoelectric basis

Pros

1. Works well for materials with effective-Z between 5 and 18
    1. Relative absolute error is < 1.3%
2. Mostly commonly used and well-understood

Cons

1. Does not correctly measure the Compton or photoelectric coefficients
2. Photoelectric coefficient is noisy, which limits it practical use

Roder, Proc. SPIE, 1979

Basis Materials

Pros

1. Coefficients have some physical relevance, e.g., C and Al
    1. Interpolates well within narrow range, relative error is < 0.4%
2. Noise levels of coefficients roughly match noise levels of measured data

Cons

1. Error increases rapidly outside narrow range

Principal Component Analysis (PCA) Basis

- Effectiveness of multi-energy basis approximation driven by the following approximation

$$\mu(E,x) \approx \sum_i b_i(E)c_i(x)$$

- We may choose a basis by minimizing the error in the above approximation for a specified range of materials
- Principal Component Analysis enables us to choose the *best* basis possible because it minimizes the Mean Square Error
  - 3-element PCA basis derived from LAC values of Z = 6, 7, 8, 13, 26, 36; relative absolute error is < 1% from Z range 5 to 35
  - While Compton, photoelectric, iron bases error is < 3% from Z range 5 to 35

Transformation to LAC/ Mono-Energy Basis

LAC basis is simply a **linear transformation** of any given basis, e.g., Compton/ photoelectric, material basis, etc

To use LAC basis, one must choose a basis and a pair of energies, E_1 and E_2

Then basis coefficients are LAC values at E_1 and E_2

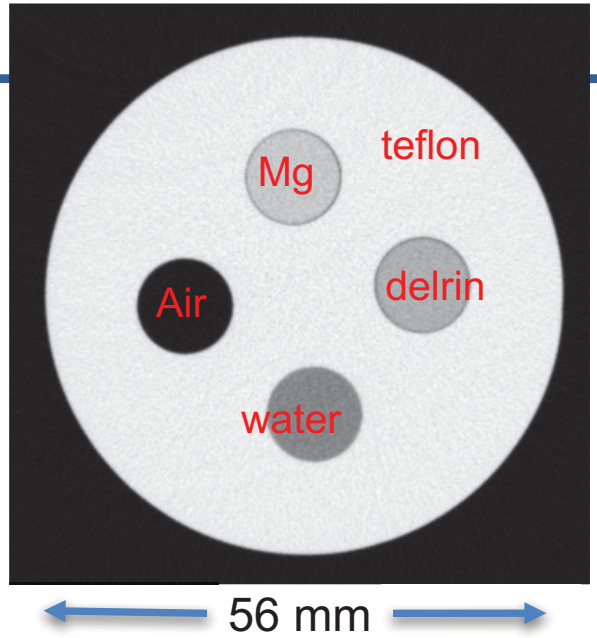
$$\mu(E,x) \approx b_1(E)\mu_1(x) + b_2(E)\mu_2(x)$$
$$\mu(54,x) \approx 0\mu_1(x) + 1\mu_2(x)$$
$$\mu(95,x) \approx 1\mu_1(x) + 0\mu_2(x)$$

No matter what basis is used, transformation to LAC basis gives you:

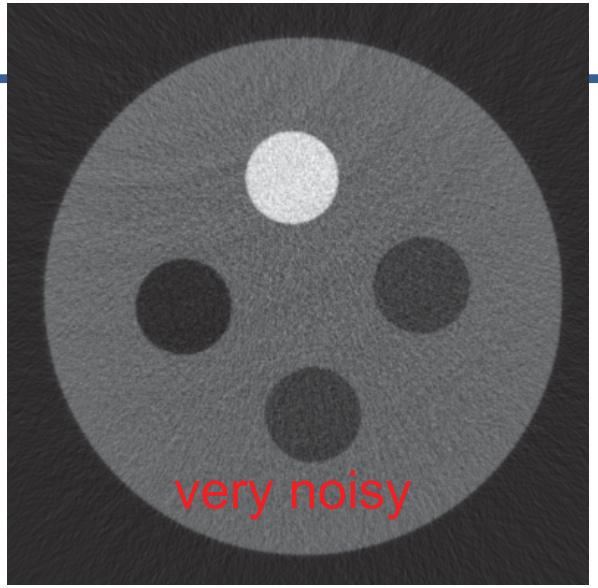
- Basis functions that are unitless
- Basis coefficients that are in LAC units (mm^{-1})

Comparison of Compton/ photoelectric and LAC basis results with Real Measured Data

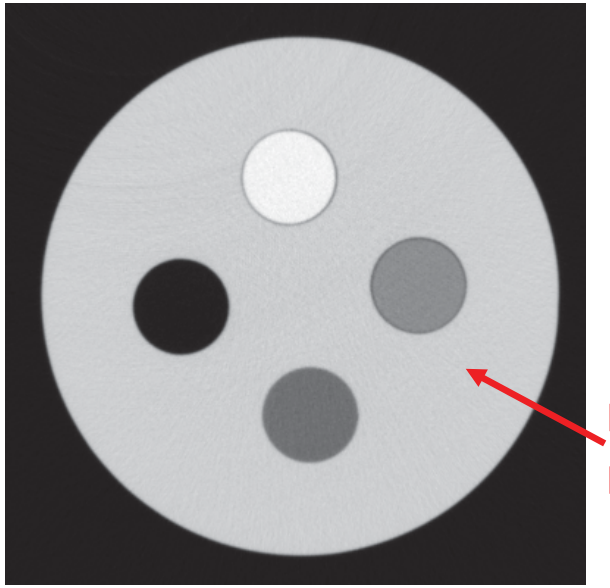
Compton coefficient



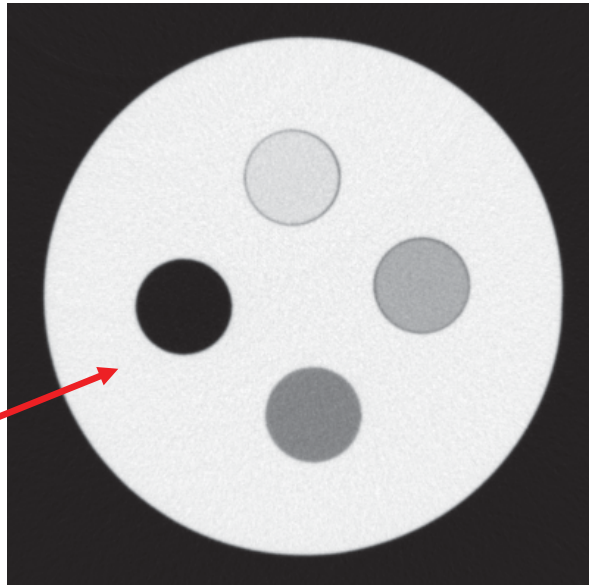
Photoelectric coefficient



LAC at 44 keV



LAC at 88 keV



noise levels roughly equivalent

Adaptive Dual-Energy Decomposition

Form multiple LAC bases from different basis representations, e.g. bases composed of all pairs of elements that could be present in luggage

For each dual-energy measurement, perform multi-energy decomposition with each LAC basis and choose the result with the lowest residual error

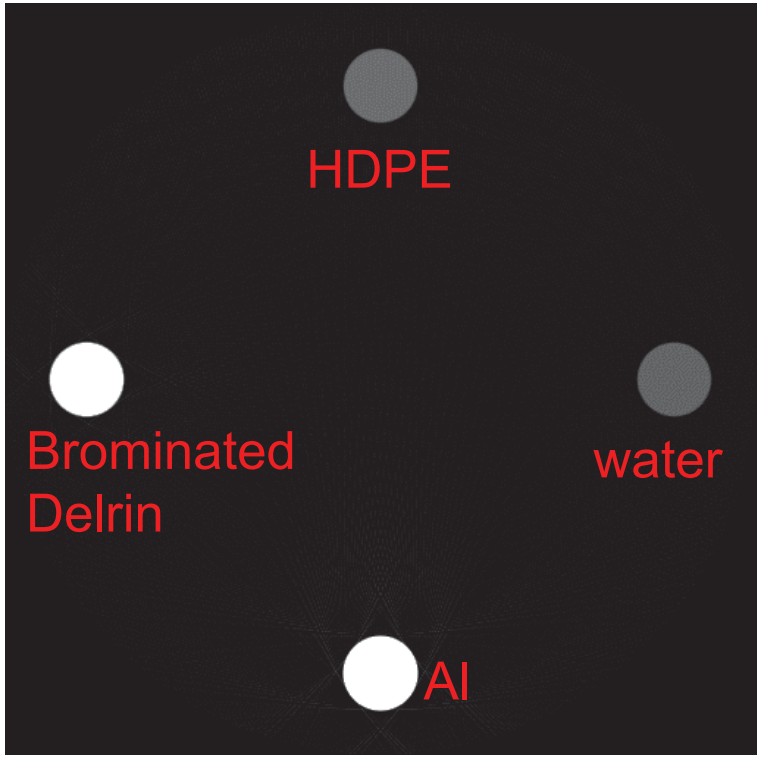
Thus each ray-sum measurement pair could be decomposed using a different set of basis materials

LAC basis is necessary because it maps all bases to a common unit system that can be reconstructed; you cannot reconstruct if each measurement pair lies in a different space

Dual-Energy Decomposition Experiment with Simulated Polychromatic Data

Spectrum 1:
100 kV, 2 mm Al filter

Spectrum 2:
160 kV, 2 mm Al, 2 mm Cu filters



all objects have 1” diameter

Dual Energy Decomposition Results

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LAC basis derived from PCA performed on par with
LAC basis derived from Compton/ photoelectric basis

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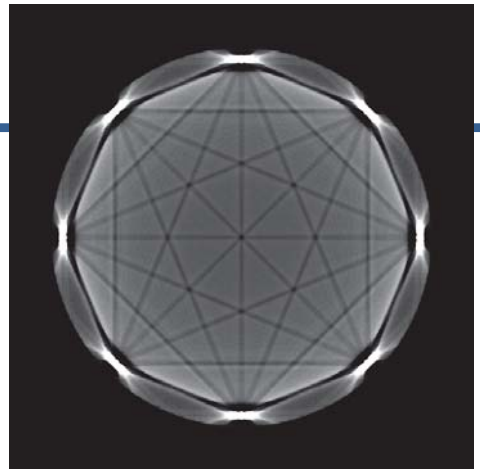

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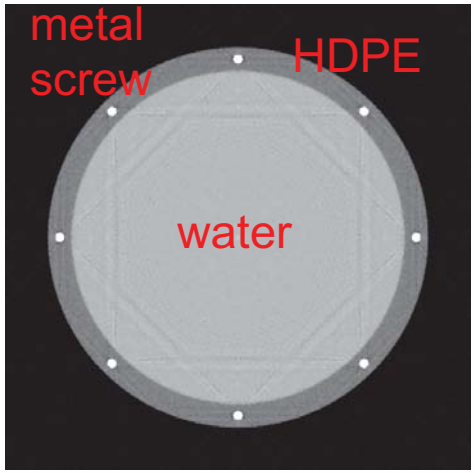

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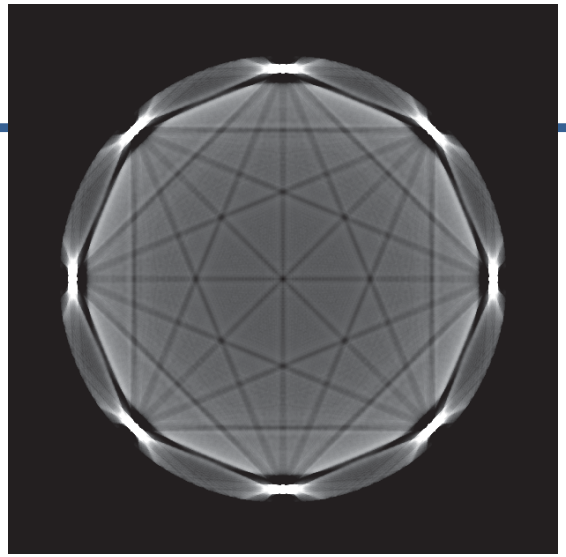
Questions?

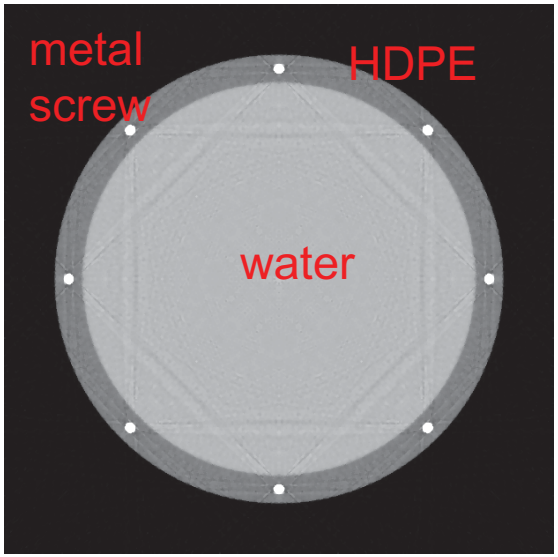
Backup Slides

Multi-Spectral CT for Baggage Inspection

Single Energy Reconstruction



Dual Energy Reconstruction



Provides more material features and reduces artifacts

- better material discrimination
- improved accuracy and precision
- lower P_{FA}/ higher P_D

Current methods

- work well for materials with a narrow range of atomic number
- do not provide results with specified units

We develop new multi-spectral methods that produce results with specified units and are accurate for materials with a wider range of atomic number

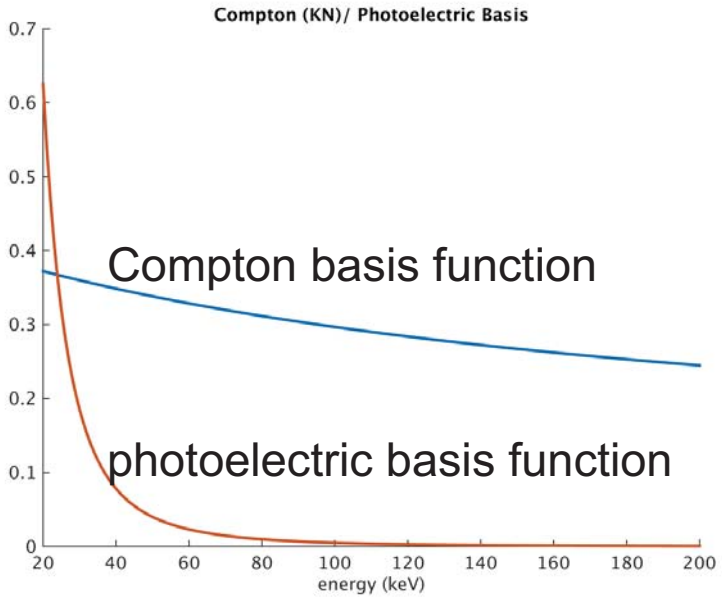
Common Dual-Energy Models

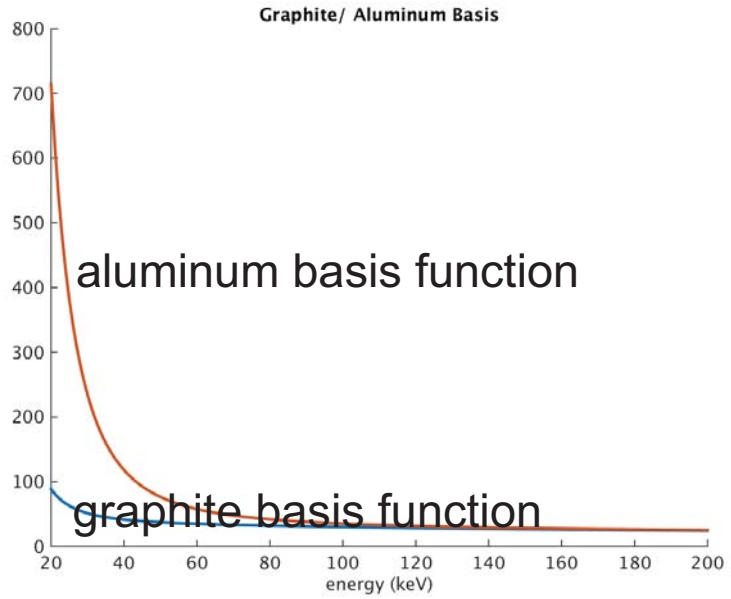
Compton/ Photoelectric Basis

Compton basis function is based on the total Klein-Nishina cross section and photoelectric basis function is E^{-3}

Basis Materials

Basis functions are the LAC curves of any two materials

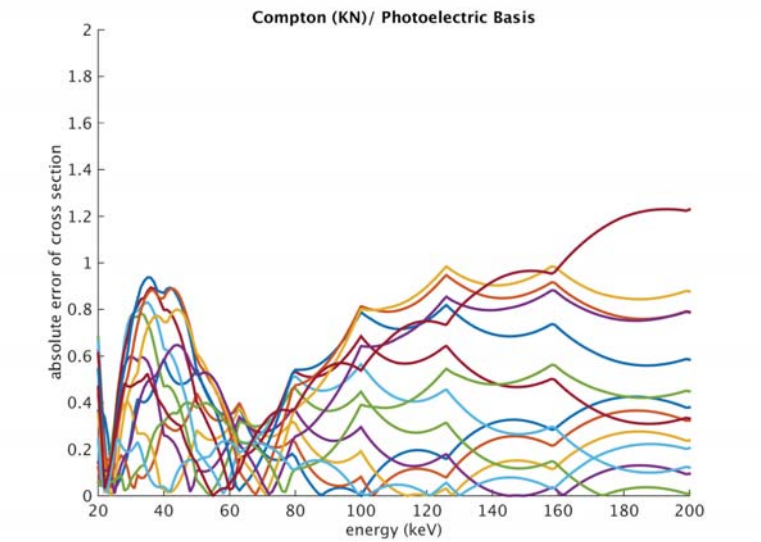


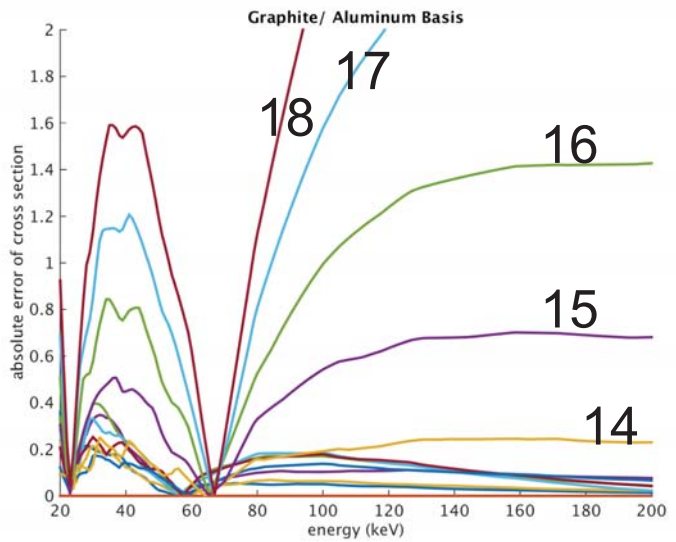


Accuracy of Common 2-Element Bases v.s. Theoretical Values

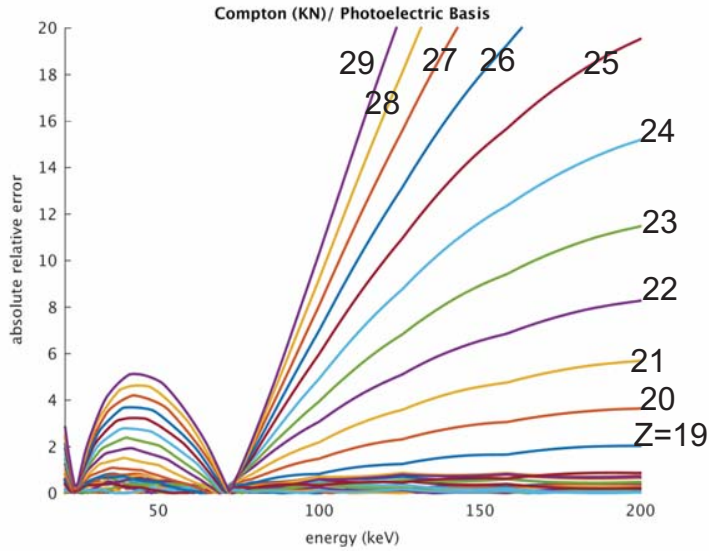
$$\text{relative error} = 100\left|\frac{Basis - Theory}{Theory}\right|$$

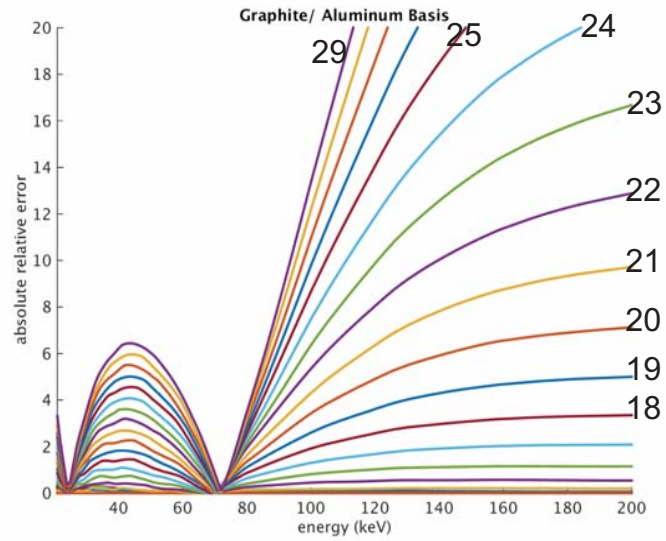
Z: 5-18





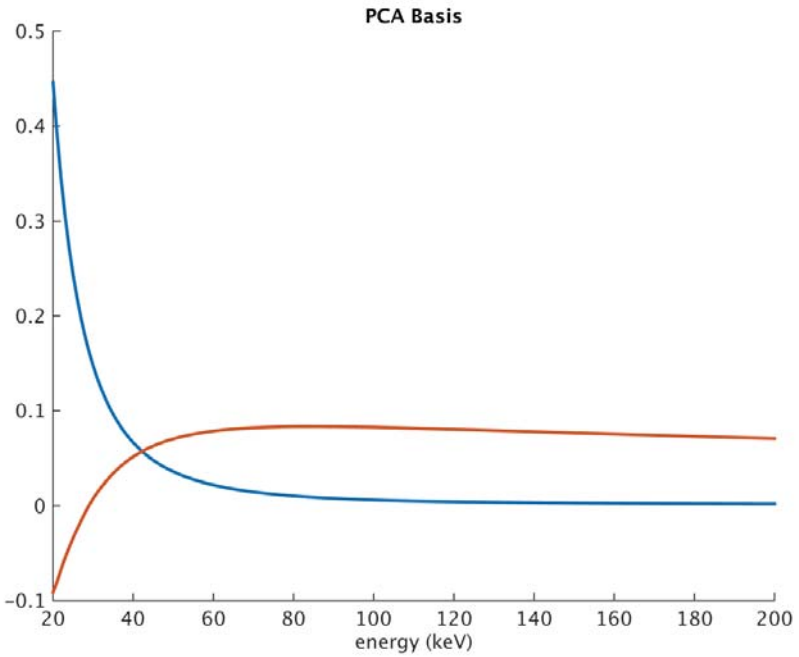
Z: 5-29





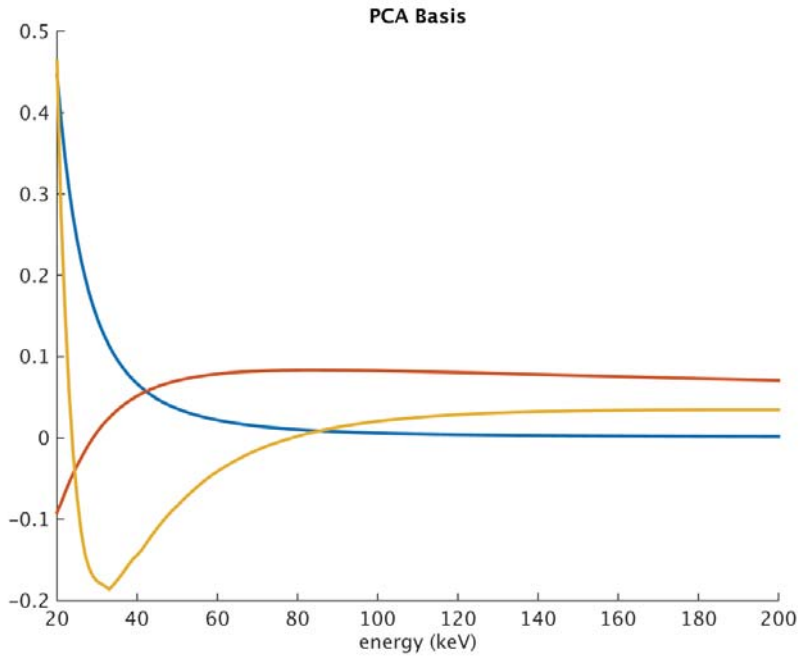
Principal Component Analysis (PCA) Basis

Dual-Energy PCA Basis



2-element PCA basis derived from LAC values of Z = 6, 7, 8, 13

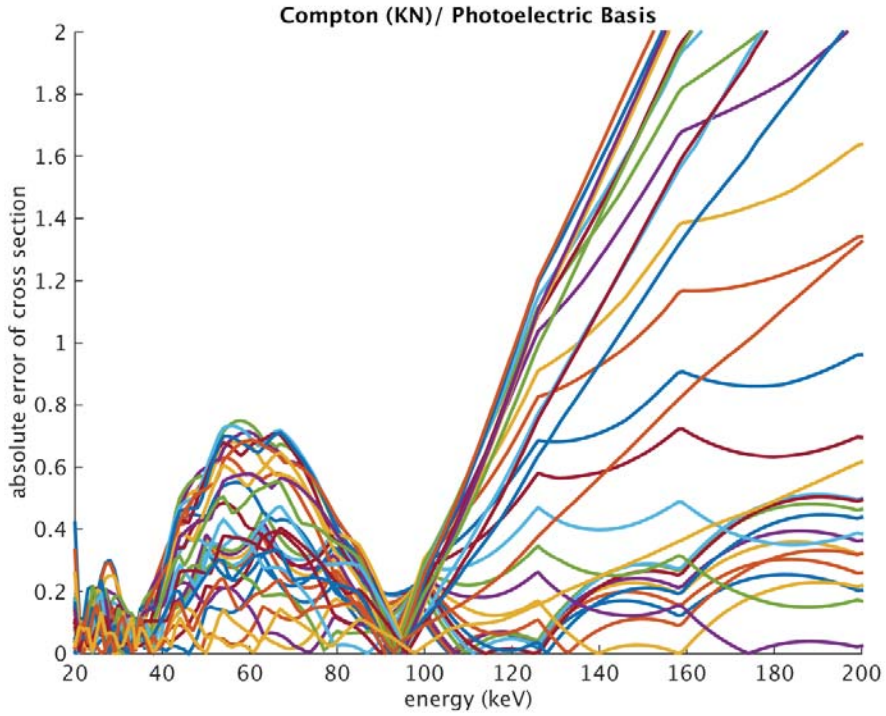
Triple-Energy PCA Basis



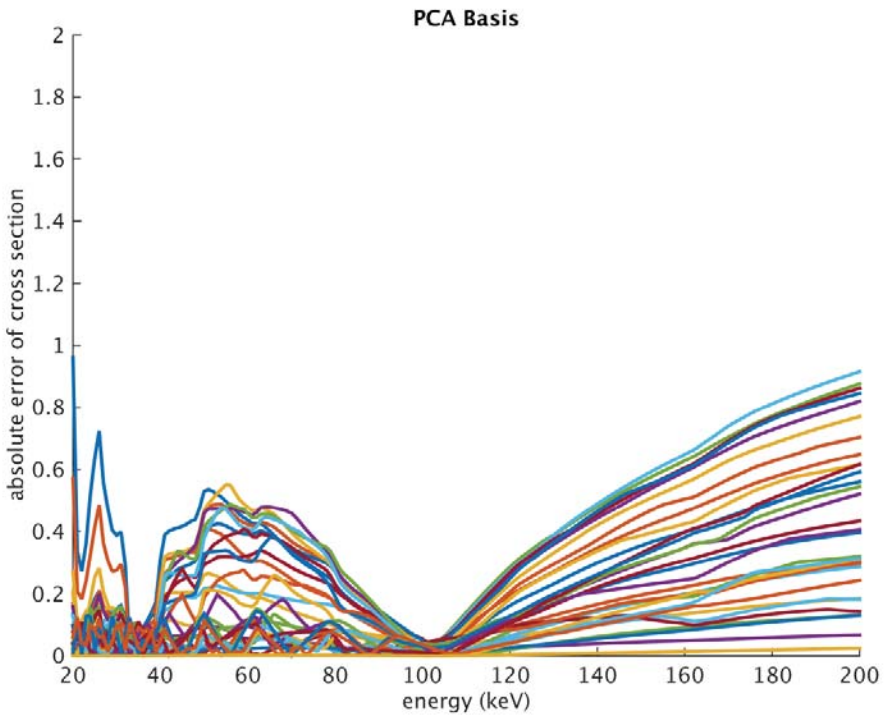
3-element PCA basis derived from LAC values of Z = 6, 7, 8, 13, 26, 36

Accuracy of 3-Element Bases for Elements 5 - 36

- Dual-energy: PCA basis does not outperform conventional bases
- Triple-energy: PCA basis outperforms conventional bases

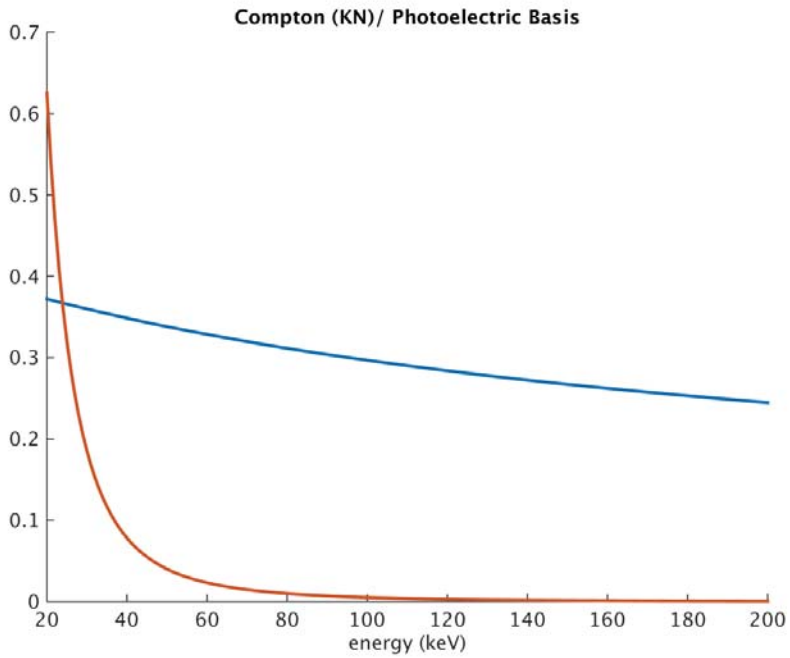


Compton, photoelectric, iron basis set

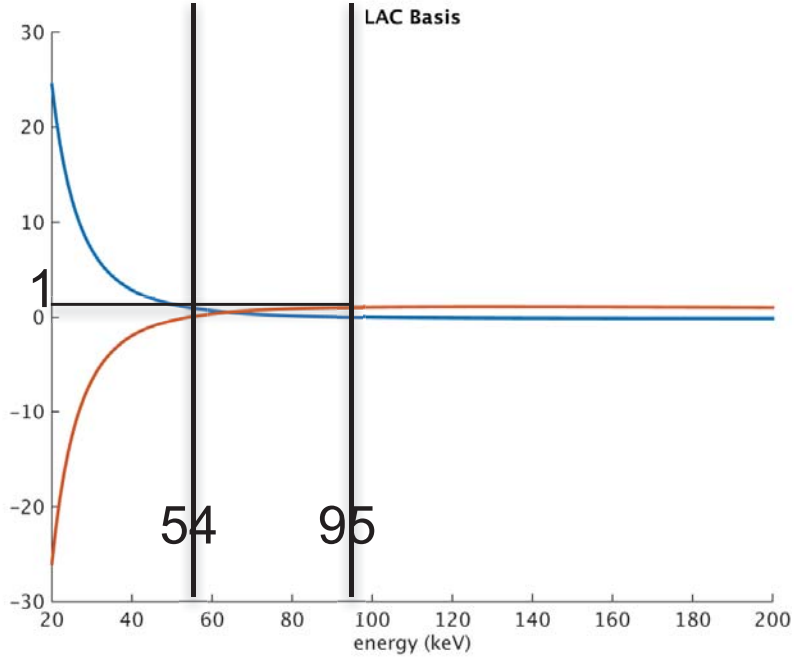


3-element PCA basis derived from LAC values of Z = 6, 7, 8, 13, 26, 36

LAC basis plots



LAC
Basis
Transformation



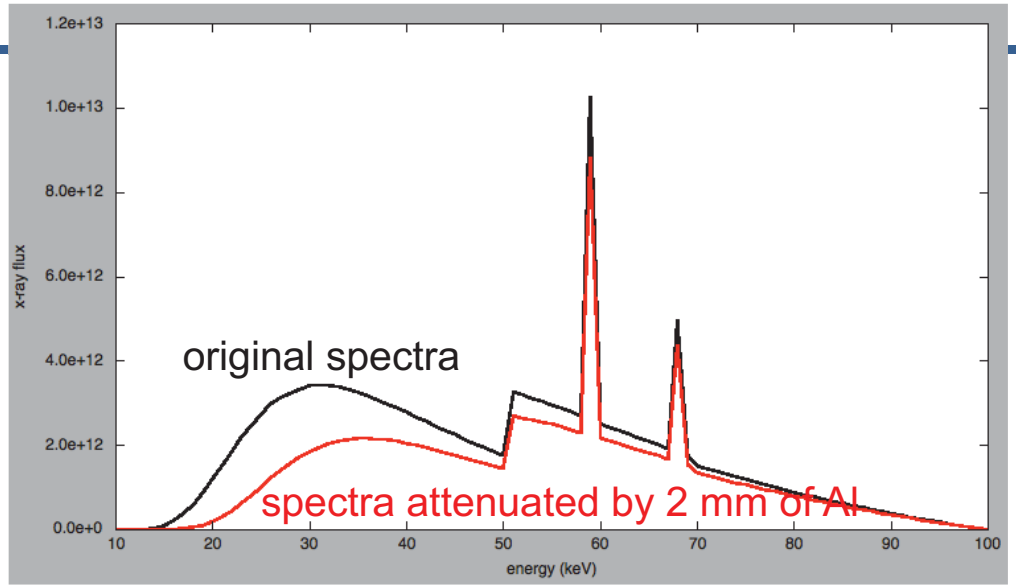
LAC basis here is a transformation of Compton/ photoelectric basis

$$\mu(E,x) \approx b_1(E)\mu_1(x) + b_2(E)\mu_2(x)$$
$$\mu(54,x) \approx 0\mu_1(x) + 1\mu_2(x)$$
$$\mu(95,x) \approx 1\mu_1(x) + 0\mu_2(x)$$

Conventional Single Energy CT

Bremsstrahlung x-ray sources provide a polychromatic spectra

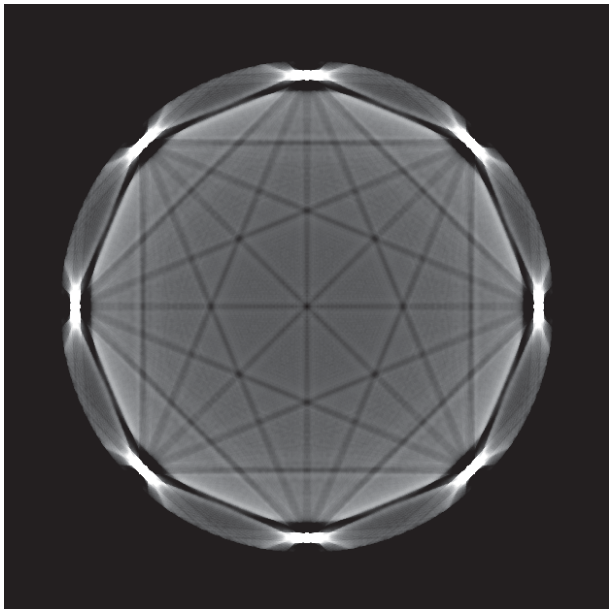
Lower energies are preferentially absorbed



Polychromatic x-ray CT is a non-linear inverse problem

Conventional methods solve a linearized approximation

Leads to cupping, streaking, loss of quantitative accuracy

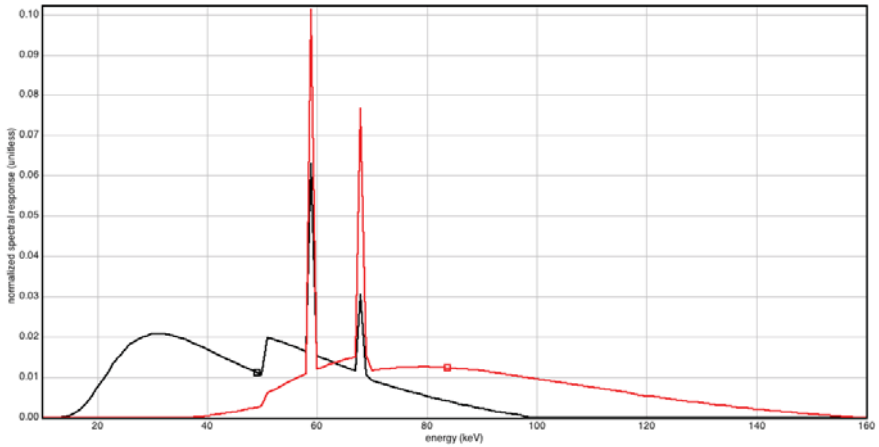


Multi-Energy CT

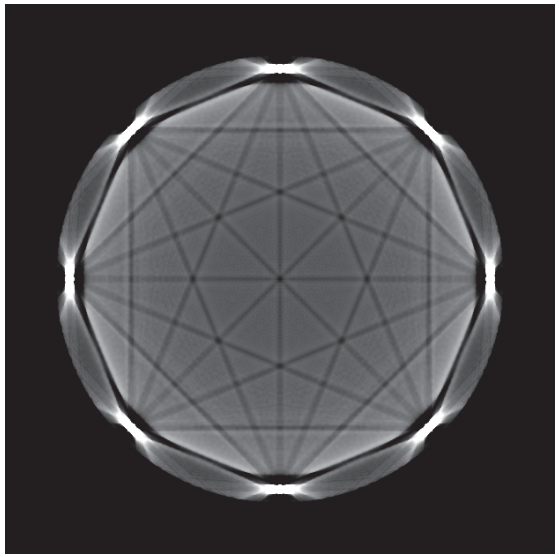
Multi-energy CT entails measuring attenuation of two or more x-ray spectra by an object

This information may be used to remove beam hardening artifacts, improve quantitative accuracy, and enable more x-ray features to be extracted

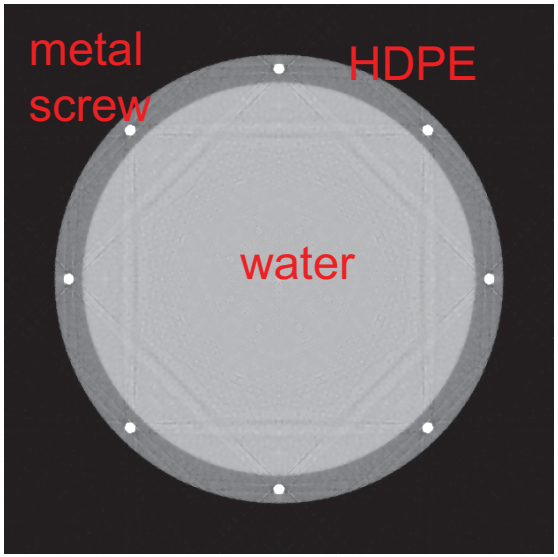
Plot of Two X-ray Spectra



Single Energy Reconstruction



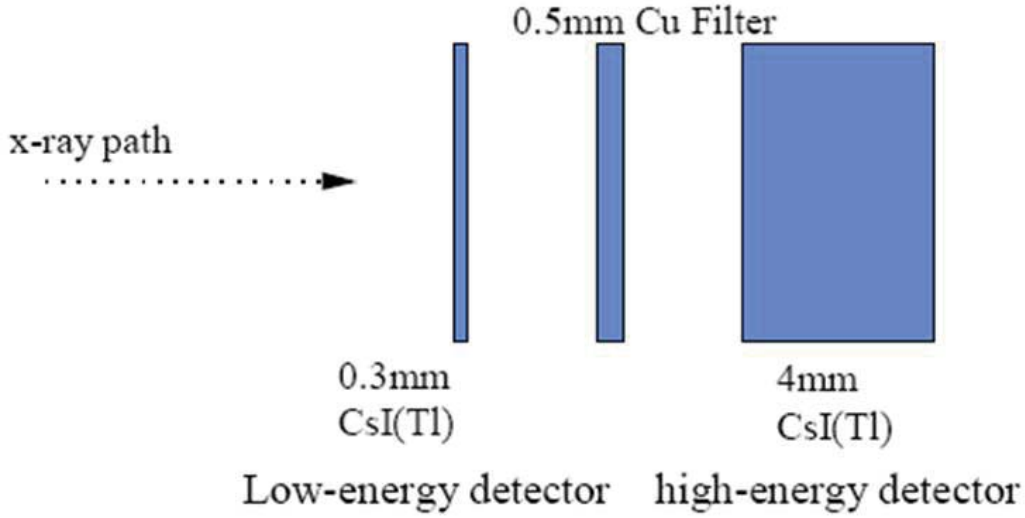
Dual Energy Reconstruction



Collecting Multi-Spectral CT Data

1. Scan same object twice with different spectra

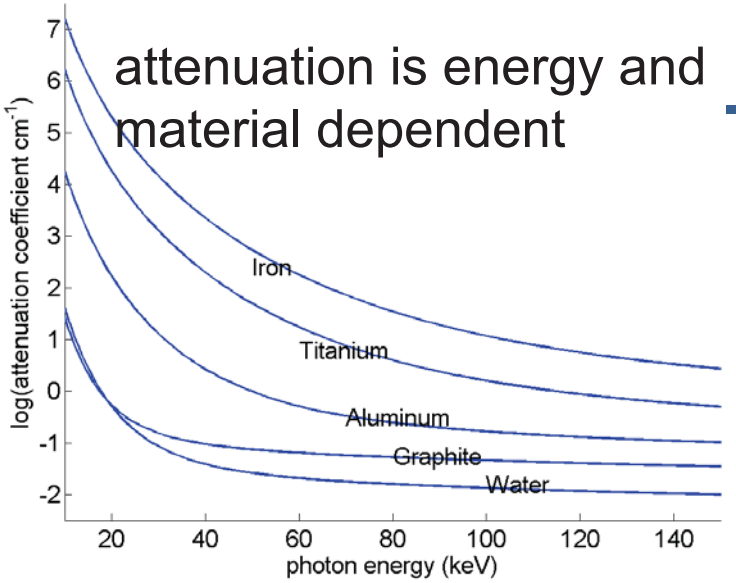
2. Sandwich detectors



3. Multi-energy spectral x-ray detector
   energy of each detected photon is estimated

Polychromatic CT Model

attenuation is energy and material dependent



spectral response

Spatial- and energy-dependent linear attenuation coefficient (LAC)

$$g = -log\left(\int s(E)e^{-\int_L \mu(E,x)dx}\, dE\right)$$

attenuation data

x-ray energy

x-ray trajectory

Three or More Energies

- Triple energy decomposition results are on par
- with adaptive basis results from previous slide

- Decomposition requires solving a non-convex cost function, so converges to local minimum with a poor initialization

- Results with high Z materials (higher than 54) are variable because low energy bins have no signal

- If using a multi-spectral detector, one may be able to use adaptive binning to ensure all channels have sufficient statistics

Approximate Polychromatic CT Model

Approximate LAC by a separable basis expansion

$$\mu(E,x) \approx \sum_i b_i(E) c_i(x)$$

Attenuation data can then be approximated by

$$g \approx -log\left(\int s(E) e^{-\sum_i b_i(E) \int_L c_i(x)\, dx}\ dE \right)$$

$$= -log\left(\int s(E) e^{-\sum_i b_i(E) a_i(L)}\ dE \right)$$

Multi-energy Decomposition

Suppose one has measured a collection of data, (g_1, …, g_N), measured with spectra (s_1, …, s_N)

Then one may decompose the data into components (a_1, …, a_N)
By minimizing the following cost function

$$C\left(\begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}\right) := \frac{1}{2}\sum_{j=1}^{N}\left[g_j + log\left(\int s_j(E)e^{-\sum_i b_i(E)a_i(L)}\ dE\right)\right]^2$$

Decomposition: (g_1, …, g_N) → (a_1, …, a_N)

Transformation to LAC basis

Consider the Compton/ photoelectric basis (b_c, b_p) and corresponding coefficients (c_c, c_p) and energy pair (E_1, E_2). Then

$$\mu(E,x) \approx b_c(E)c_c(x) + b_p(E)c_p(x)$$

We define

$$\begin{aligned}\mu_1 &:= b_c(E_1)c_c + b_p(E_1)c_p \\ \mu_2 &:= b_c(E_2)c_c + b_p(E_2)c_p\end{aligned} \quad \Rightarrow \quad \begin{bmatrix}\mu_1 \\ \mu_2\end{bmatrix} = \begin{bmatrix}b_c(E_1) & b_p(E_1) \\ b_c(E_2) & b_p(E_2)\end{bmatrix}\begin{bmatrix}c_c \\ c_p\end{bmatrix}$$

and thus

$$\begin{bmatrix}c_c \\ c_p\end{bmatrix} = \begin{bmatrix}b_c(E_1) & b_p(E_1) \\ b_c(E_2) & b_p(E_2)\end{bmatrix}^{-1}\begin{bmatrix}\mu_1 \\ \mu_2\end{bmatrix}$$

$$b_c(E)c_c(x) + b_p(E)c_p(x) = \begin{bmatrix}b_c(E) & b_p(E)\end{bmatrix}\begin{bmatrix}b_c(E_1) & b_p(E_1) \\ b_c(E_2) & b_p(E_2)\end{bmatrix}^{-1}\begin{bmatrix}\mu_1 \\ \mu_2\end{bmatrix}$$

$$=: b_1(E)\mu_1 + b_2(E)\mu_2$$

LAC Basis is Just a Linear Transformation

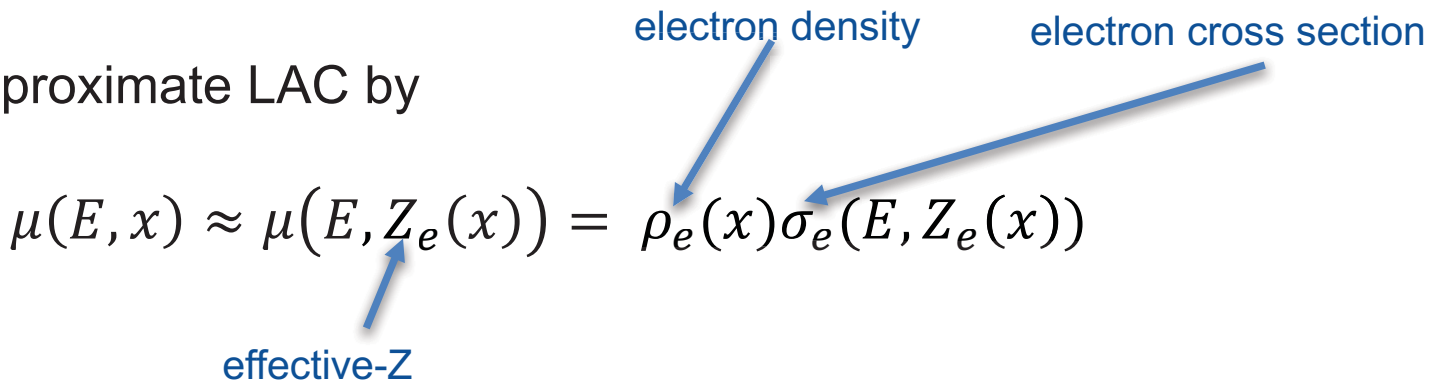
LAC basis is simply a **linear transformation** of a given basis, e.g., Compton/ photoelectric, material basis, etc

If one performs multi-energy decomposition with a given basis and then transforms to an LAC basis (with a simple matrix multiplication), one get the same result by doing the multi-energy decomposition directly with an LAC basis and vice versa

No matter what the root basis used, transformation to LAC basis will give you results in LAC units

Transforming LAC basis coefficients to Electron Density and Effective Atomic Number

One may approximate LAC by



where non-integer Z_e defined by linear interpolation

If one has dual energy data one can estimate electron density and effective atomic number (effective-Z) by solving

$$\mu_1 = \rho_e \sigma_e(E_1, Z_e)$$
$$\mu_2 = \rho_e \sigma_e(E_2, Z_e)$$

Example of a Main Title and Content [Calibri Font]

Use 24-pt “Regular” (no bold) subtitles to provide additional detail

- Laboratory budgets over the last 15 years
- How does this affect my program?
- What are the relative values of our investments? (Discussion)
- Three critical issues to be decided:
  - Size of effort
  - Organization and R2A2
  - Funding mechanisms
- Wrap-up

Summary box has a full-width bleed.
Delete if not needed.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