The Generalized NEQ and Detectability Index for Tomosynthesis and Cone-Beam CT

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Motivation

Cascaded Systems Analysis (CSA)
Extension of Fourier performance metrics (NEQ) to advanced imaging applications

NEQ → Task → Detectability Index ($d'$)
General quantitative metrics for performance assessment incorporating imaging tasks

System Performance and Optimization
Investigate the extent to which $d'$ is a valid metric for performance evaluation
→ Correspondence with real observers

J. H. Siewerdsen (Johns Hopkins University)
Bridging the Gap

Fourier Metrics (GNEQ)
Fundamental Image Science

Real Observer Response

Generalized Detectability

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Cascaded Systems Analysis

Projection Formation

0. Incident photon
1. Interact
2. Convert
3. Spread
4. Coupling
5. Aperture
6. Sample
7. Additive noise

8. Log
9. Ramp
10. Apodize
11. Interp
12. Back-projection
13. Sample

Reconstruction by Filtered Backprojection

• “Generalized” Detectability Index

\[ d_{3D}^2 = \int \int \int \frac{[T \cdot W_{Task}]^2}{T^2 S_B + S_Q + S_E} df_x df_y df_z \]

\[ S_B = \frac{\kappa}{f^\beta} \]

- \( S_B \) - Anatomical background power spectrum (Power-law)

- \( T \) – System MTF
- \( W_{Task} \) – Imaging task
- \( S_Q \) – Quantum NPS
- \( S_E \) – Electronics NPS

J. H. Siewerdsen (Johns Hopkins University)
Model Observers ($d'$)

- Prewhitening observer (PW)

\[
d'^2 = \int \int \int \frac{[T \cdot W_{\text{Task}}]^2}{(T^2 S_B + S_Q + S_E)} \, df_x \, df_y \, df_z
\]
Model Observers ($d'$)

- Prewhitening observer (PW)
- PW observer with eye filter and internal noise (PWEi)

\[
d'^2 = \int \int \int \frac{\left[ T \cdot W_{\text{Task}} \right]^2}{\left( T^2 S_B + S_Q + S_E \right)} df_x df_y df_z
\]
Model Observers ($d'$)

- Prewhitening observer (PW)
- PW observer with eye filter and internal noise (PWEi)
- Non-prewhitening observer (NPW)

\[
d'^2 = \frac{\left[ \int \int \int [T \cdot W_{Task}]^2 df_x df_y df_z \right]^2}{\int \int \int (T^2 S_B + S_Q + S_E) \cdot [T \cdot W_{Task}]^2 df_x df_y df_z}
\]

J. H. Siewerdsen (Johns Hopkins University)
Model Observers ($d'$)

- Prewhitening observer (PW)
- PW observer with eye filter and internal noise (PWEi)
- Non-prewhitening observer (NPW)
- NPW observer with eye filter (NPWE)

\[
d'^2 = \frac{\int \int \int \left[ \int \int \int \left[ T \cdot W_{Task} \right]^2 \, df_x \, df_y \, df_z \right]^2 \, df_x \, df_y \, df_z}{\int \int \int (T^2 S_B + S_Q + S_E) \cdot \left[ T \cdot W_{Task} \right]^2 \, df_x \, df_y \, df_z}
\]

J. H. Siewerdsen (Johns Hopkins University)
Model Observers ($d'$)

- Prewhitening observer (PW)
- PW observer with eye filter and internal noise (PWEi)
- Non-prewhitening observer (NPW)
- NPW observer with eye filter (NPWE)
- NPWE observer with internal noise (NPWEi)

$$d'^2 = \frac{\left[ \iiint E^2 [T \cdot W_{Task}]^2 df_x df_y df_z \right]^2}{\iiint \iiint E^4 (T^2 S_B + S_Q + S_E) \cdot [T \cdot W_{Task}]^2 df_x df_y df_z}$$

J. H. Siewerdsen (Johns Hopkins University)
Model Observers ($d'$)

- Prewhitening observer (PW)
- PW observer with eye filter and internal noise (PWEi)
- Non-prewhitening observer (NPW)
- NPW observer with eye filter (NPWE)
- NPWE observer with internal noise (NPWEi)

“Slice” Detectability Index

- Integrate over direction orthogonal to slice

$$d'_{\text{slice}}^2 = \int \int \frac{\left[ \int T \cdot W_{\text{Task}} df_y \right]^2}{\int T^2 S_B + S_Q + S_E df_y} df_x df_z$$

J. H. Siewerdsen (Johns Hopkins University)
Experimental Conditions

A Clutter Phantom for Power-Law Noise

Design principle: self-similarity

Equal volumes of differently-sized spheres

\[ S_B = \frac{K}{f^{\beta}} \]

\[ \beta \approx 3 \] radiograph

\[ \beta (\theta_{tot}) \] tomosynthesis and CBCT

TWO Scenarios:

Variable \( \theta_{tot} \)

\textbf{Constant} \( \Delta \theta \)

\[ \Delta \theta = 0.45^\circ \]

Variable total dose

\textbf{Constant} \( N_{proj} \)

\[ N_{proj} = 89 \]

Fixed total dose

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Imaging Tasks

Clutter Phantom
Six stimuli in the central coronal (x-z) slice

Uniform Background Phantom
Acrylic sphere on polyurethane background

Five Imaging Tasks

Sphere Detection in Uniform Background
Small Sphere Detection
Large Sphere Detection
Cube vs. Sphere Detection
Encapsulated Sphere vs. Solid Sphere

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Observer Study – 9 AFC

Human Observer Measurements

9-Alternative Forced-Choice (AFC) Test
Darkened reading room
Monochrome diagnostic-quality display
Fixed \text{win} / level \[90\% \text{min}, 110\% \text{max}\]
8 observers (physicists)
Training set distinct from test set
5 trials (distinct stimuli)
Randomized reading order
\sim 100 \text{ minutes for each observer}
Observer Study – 9 AFC

Theoretical calculation
(cascaded systems + task + model observer)

\[ A_z = \frac{1}{2} (1 + \text{erf}(\frac{d'}{2})) \]

\[ P_{corr}(d', M) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(-\frac{(x-d)^2}{2}\right)[\phi(x)]^{M-1} \, dx \]

Measured directly from human observer MAFC tests

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Theory vs. Measurement

1. Sphere Detection on Uniform Background

Question to observer:
Which image contains a \(\frac{1}{4}\)" sphere at the center

\[ W_{\text{Task}} \]

\[ f_x, f_z \]

\[ 10^0, 40^0, 120^0, 200^0, 280^0, 360^0 \]

Constant \(\Delta\theta\)

\[ A_z \]

\[ 0.4, 0.6, 0.8, 1.0 \]

\[ 0, 60, 120, 180, 240, 300, 360 \]

J. H. Siewerdsen (Johns Hopkins University)
Theory vs. Measurement
1. Sphere Detection on Uniform Background

Question to observer:
Which image contains a ¼” sphere at the center

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Theory vs. Measurement
2. Small Sphere Detection on Cluttered Background

Question to observer:
Which image has a high contrast 1/8” sphere at the center

Constant $\Delta \theta$

Human Observer

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Theory vs. Measurement

2. Small Sphere Detection on Cluttered Background

Question to observer:
Which image has a high contrast 1/8” sphere at the center

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Theory vs. Measurement

5. Encapsulated Sphere vs. Solid Sphere

Question to observer:
Which image has a ½” diameter encapsulated sphere at the center

J. H. Siewerdsen (Johns Hopkins University)
5. Encapsulated Sphere vs. Solid Sphere

Question to observer:
Which image has a ½” diameter encapsulated sphere at the center?
Conclusions

• Detectability Index (d’)
  – GNEQ + Imaging Task + Observer Model(s)
  – Shown to provide a valid metric for imaging performance and system optimization

• Assumptions and Limitations
  – Stationarity (local NPS – image center or fixed radius)\(^1\)
  – Shift-invariance (task > voxel size)\(^2\)
  – Simple, idealized imaging tasks

• Future Work
  – Broader range of imaging conditions (dose) and reconstruction techniques (binning and sampling)
  – More complex (higher order) imaging tasks

\(^1\) Pineda (SPIE 2007)
\(^2\) analogous to Albert and Maidment (Med Phys 2000)
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