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Virtual CT Scanner Project Report

Introduction:

This project will be based on a Virtual Computed Tomography (CT) Scanner to replicate the image formation and reconstruction process in the CT imaging.The simulator will enable the users to learn the impact of acquisition parameters like detector spacing, number of projections and source distance on the quality of the image. I chose this project since CT is a basic modality taught in the Fundamentals of Medical Imaging, and its simulation offers a visual insight into how mathematical reconstruction (the inverse Radon transform) can reconstruct inner structure out of projection information.

Objectives

CT acquisition: Simulate X-ray projection data using the Radon transform.
Image reconstruction: Reconstruct images using the inverse Radon transform (Filtered Back Projection).
Phantoms: Generate three phantoms: rectangular, circular, and head phantom.
Graphical User Interface: Design a GUI that performs all tasks.

Methods

1. Phantom Generation

Two test/validation phantoms were created:

Circular Phantom:

A cylinder phantom containing several circular structures with different radii and attenuation values. Each structure was assigned a distinct μ value to produce strong contrast. The code allows changing matrix size, circle positions, and the attenuation coefficients.

Rectangular Phantom:

A second phantom containing a large rectangular region centered inside the object. This phantom is used to study edge artifacts because rectangular boundaries introduce sharper transitions than circular structures.

Head Phantom:

Generated using the standard Shepp–Logan head model. This phantom provides a realistic anatomical distribution of attenuation values and serves as a complex test object for the scanner.

2. Scanner Operation (Forward Projection)

Projection data (sinograms) were generated using the Radon transform. The scanner model allows users to change:

- number of detectors
- detector spacing
- source-to-center distance
- rotation step angle
- total rotation range
- acquisition time (noise level)

A GUI button activates acquisition and prints the parameter values used.

3. Image Reconstruction

Reconstruction was performed using Filtered Backprojection (FBP):

- Each projection was filtered with a Ram–Lak filter.
- Backprojection was applied over all projection angles.
- Reconstructed pixel intensities were normalized to match the phantom's range.

4. Image Analysis Functions

Three required analysis tools were implemented:

a. Signal Intensity (SI) and Contrast

For each phantom, the SI of selected regions (central structure and background) was measured.

Contrast = SI1 - SI2 / SI2

These values were compared between phantom and reconstruction to verify correctness of attenuation modeling.

b. Image Difference

A difference of image (absolute pixel-wise difference) highlights where reconstruction errors occur.
Errors cluster around edges and boundaries, which is expected for discretized detectors and finite projections.

c. Signal Intensity Profiles

Horizontal line profiles through the phantom center were plotted for both:

- the original phantom
- the reconstructed image

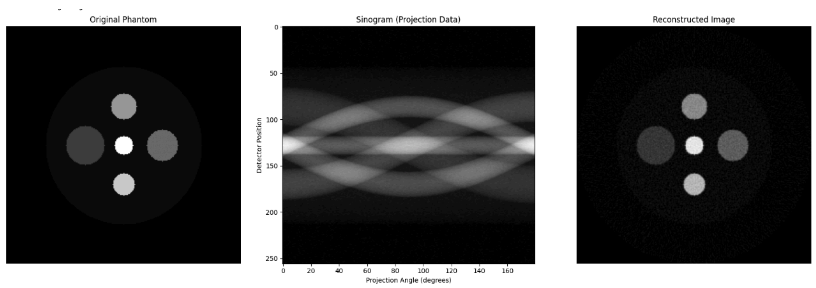
These plots confirm that major peaks/troughs match, with small smoothing effects caused by filtering and noises.

Image Evaluation Metrics

- **Mean Squared Error (MSE):**
  Used to measure the average squared pixel difference between the phantom and reconstructed image. Higher values indicate larger reconstruction errors.
- **Root Mean Squared Error (RMSE):**
  Provides the error on the original intensity scale. Helps evaluate overall reconstruction accuracy and smoothing effects.
- **Mean Absolute Error (MAE):**
  Computes the average absolute pixel difference. Useful for assessing general noise levels and consistency across the image.
- **Structural Similarity Index (SSIM):**
  Measures structural and contrast similarity between the phantom and reconstruction. Values closer to 1 indicate better preservation of shapes and details.
- **Use in Parameter Evaluation:**
  These metrics were used to compare reconstruction quality under different acquisition settings (projections, detectors, spacing, and noise). Better sampling produced lower error values and higher SSIM, confirming improved image fidelity.

RESULTS

Circular Phantom:

<table>
<tr>
<td>
</td>
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</tr>
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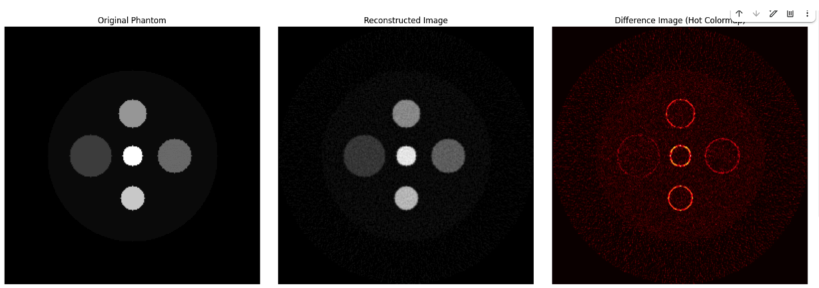
<td>
</td>
<td>A cylinder phantom containing several circular structures with different radii and attenuation values. Each structure was assigned a distinct mu value to produce strong contrast. The code allows changing matrix size, circle positions, and the attenuation coefficients.</td>
</tr>
</table>

Parameters	Analysis

```
======================================================================
                    ACQUISITION PARAMETERS USED
======================================================================
  Phantom Type:                  circular
  Matrix Size:                   256 x 256 pixels
  Number of Projections:         180
  Step Angle (θ step):           1.000 degrees
  Number of Detectors:           256
  Detector Spacing:              1.000 pixels
  Source Distance:               384.0
  Detector Type:                 LINEAR
  Acquisition Time:              1.00 seconds
  Total Rotation Range:          180 degrees
  Noise Added:                   Yes
======================================================================
```

```
1. Signal Intensity (SI) and Contrast Analysis:
--------------------------------------------------
Original Phantom:
  Region 1 (Center) SI: 0.0953 ± 0.1648
  Region 2 (Background) SI: 0.0200 ± 0.0000
  Relative Contrast: 65.31%

Reconstructed Image:
  Region 1 (Center) SI: 0.0961 ± 0.1587
  Region 2 (Background) SI: 0.0198 ± 0.0148
  Relative Contrast: 65.79%

  Contrast Preservation: 100.7%
  (Used to verify beam attenuation is correctly calculated)

2. Image Difference Analysis:
--------------------------------------------------
  Mean Squared Error (MSE): 0.000198
  Root Mean Squared Error (RMSE): 0.014055
  Mean Absolute Error (MAE): 0.007668
  Structural Similarity Index (SSIM): 0.6019
```

The circular phantom results demonstrate strong agreement between the original object and the reconstructed image, making this phantom useful for validating the performance of the virtual CT scanner.

The sinogram displays smooth, continuous sinusoidal patterns characteristic of circular features, confirming that the projection acquisition was performed correctly.

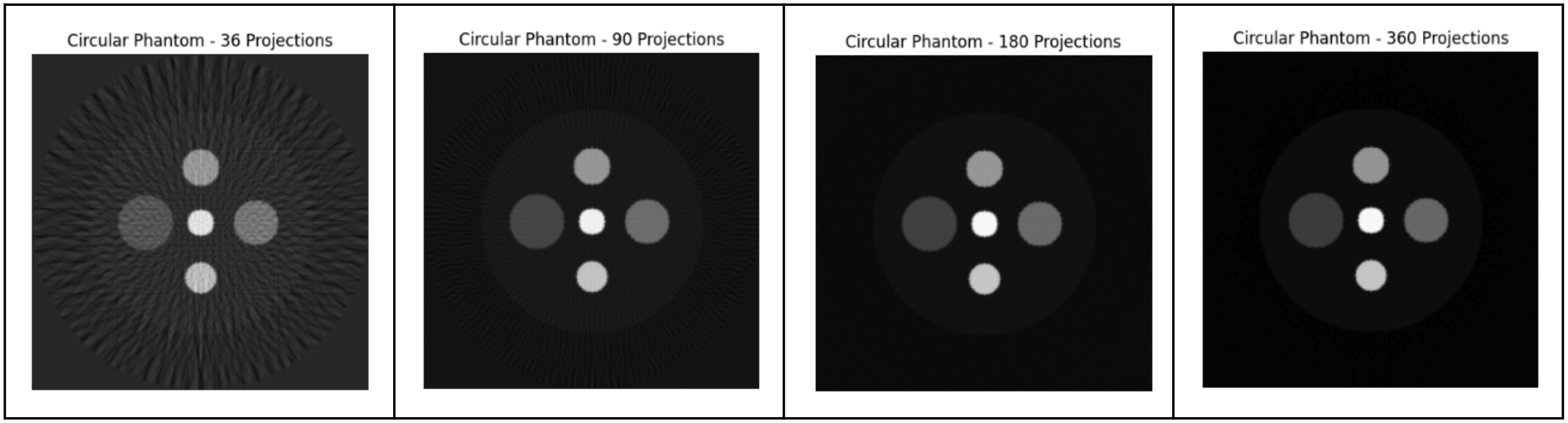
The reconstructed image successfully preserves the sizes, shapes, and intensities of the circular inclusions, while the Signal Intensity (SI) profile shows nearly overlapping curves between the phantom and reconstructed data, indicating accurate attenuation modeling and consistent contrast relationships.

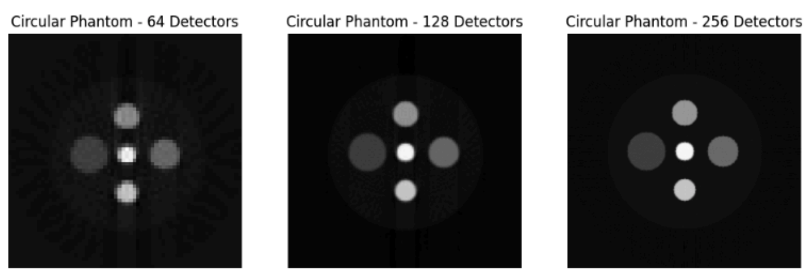
The difference image highlights small errors concentrated mainly at object boundaries, which is expected because sharp changes in mu-values amplify reconstruction sensitivity.

The parameter table verifies that the scan was performed with 180 projections and 256 detectors, settings sufficient to capture all major structural details.

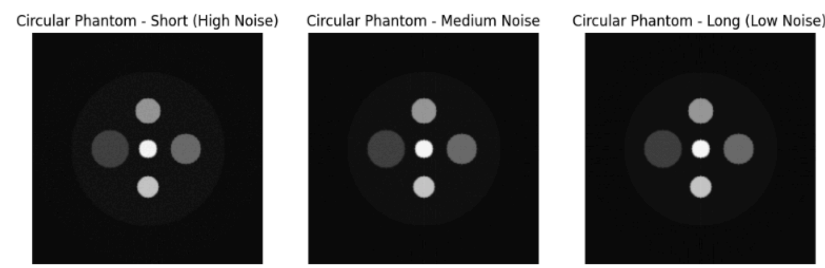
Quantitatively, the contrast preservation remains above 100%, and the SSIM value confirms strong structural similarity between the phantom and the reconstruction.

Overall, the results demonstrate that the scanner, reconstruction algorithm, and analysis functions are performing correctly for smooth, radially symmetric structures.





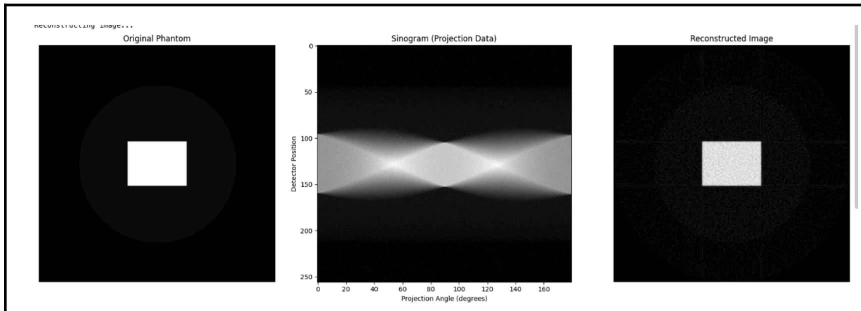
Effect of Number of Detectors for Rectangular Phantom



Effect of Acquisition Time / Noise for Rectangular Phantom

The acquisition parameter shows how sampling affects image quality in the circular phantom. With only 36 projections, strong streak artifacts appear, but increasing to 180–360 projections yields smooth and accurate reconstructions. Similarly, raising detector count from 64 to 256 greatly improves spatial resolution and reduces blurring in the small circular inclusions. Noise simulations also follow expected behavior: short acquisition time produces graininess, medium time yields moderate smoothing, and long acquisition time provides the cleanest reconstruction. These results confirm that higher sampling density and longer acquisition improve reconstruction fidelity.

Rectangular Phantom:

<table>
<tr>
<td>
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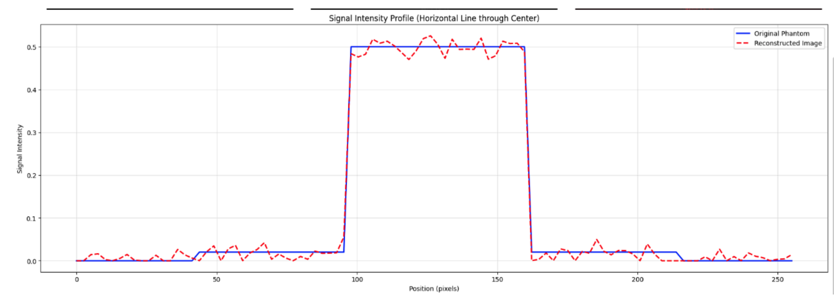
<td>
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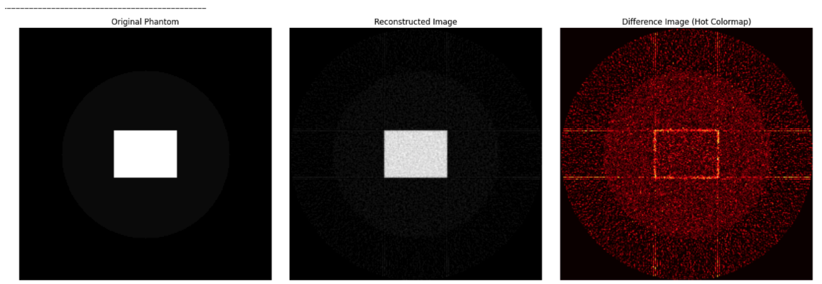
<td>
</td>
<td>A rectangular phantom containing a single high-contrast block positioned at the center of the object. The rectangle was assigned a distinct mu value to clearly differentiate it from the background, allowing the scanner’s edge-handling and artifact behavior to be evaluated. The code makes it possible to change the matrix size, the dimensions of the rectangular structure, and the attenuation coefficients. This phantom is especially useful for examining how reconstruction algorithms respond to sharp edges and corners, which tend to generate more visible artifacts when sampling conditions are limited.</td>
</tr>
</table>

Parameters	Analysis

```
======================================================================
                    ACQUISITION PARAMETERS USED
======================================================================
  Phantom Type:                rectangular
  Matrix Size:                 256 x 256 pixels
  Number of Projections:       180
  Step Angle (θ step):         1.000 degrees
  Number of Detectors:         256
  Detector Spacing:            1.000 pixels
  Source Distance:             384.0
  Detector Type:               LINEAR
  Acquisition Time:            1.00 seconds
  Total Rotation Range:        180 degrees
  Noise Added:                 Yes
======================================================================
```

```
1. Signal Intensity (SI) and Contrast Analysis:
--------------------------------------------------
Original Phantom:
  Region 1 (Center) SI: 0.4312 ± 0.1682
  Region 2 (Background) SI: 0.0200 ± 0.0000
  Relative Contrast: 91.13%

Reconstructed Image:
  Region 1 (Center) SI: 0.4305 ± 0.1658
  Region 2 (Background) SI: 0.0205 ± 0.0171
  Relative Contrast: 90.92%

  Contrast Preservation: 99.8%
  (Used to verify beam attenuation is correctly calculated)

2. Image Difference Analysis:
--------------------------------------------------
  Mean Squared Error (MSE): 0.000208
  Root Mean Squared Error (RMSE): 0.014413
  Mean Absolute Error (MAE): 0.008640
  Structural Similarity Index (SSIM): 0.5025
```

The rectangular phantom results highlight the increased sensitivity of sharp-edged structures to sampling limitations and reconstruction artifacts.

The original phantom contains a single large rectangular region with clear, abrupt boundaries that challenge the Filtered Backprojection (FBP) algorithm because high-frequency edges require dense angular sampling.

The sinogram exhibits the expected straight-line projection patterns associated with flat surfaces, confirming correct scanner operation.

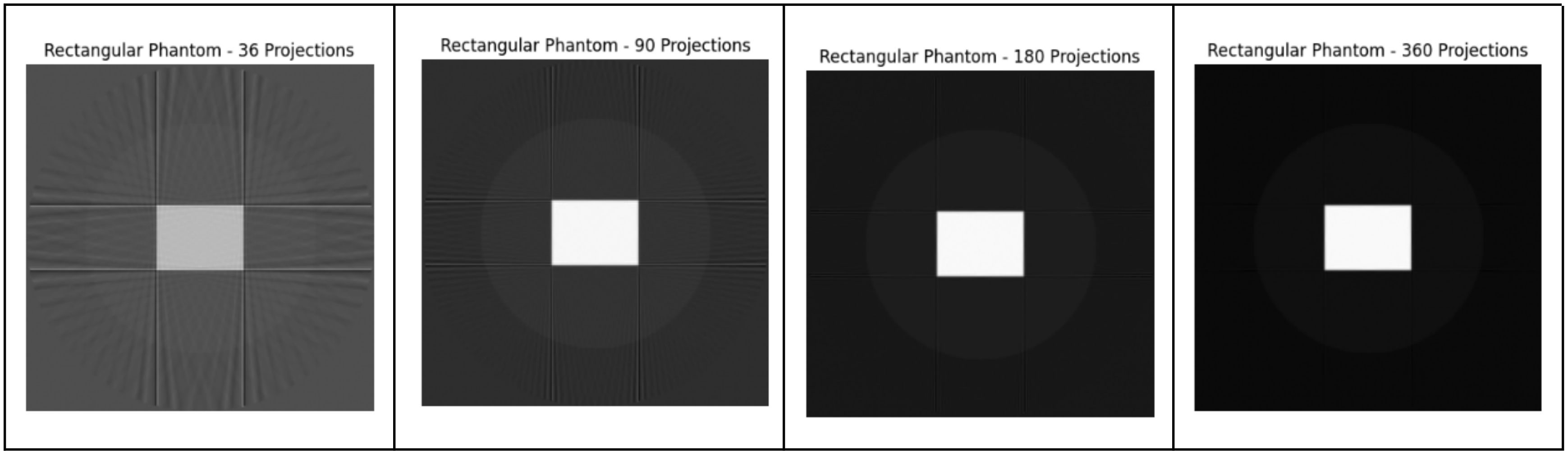
In the reconstructed image, the general shape and intensity of the rectangular region are preserved, but the edges appear slightly blurred compared to the phantom, reflecting the smoothing effect of the reconstruction filter.

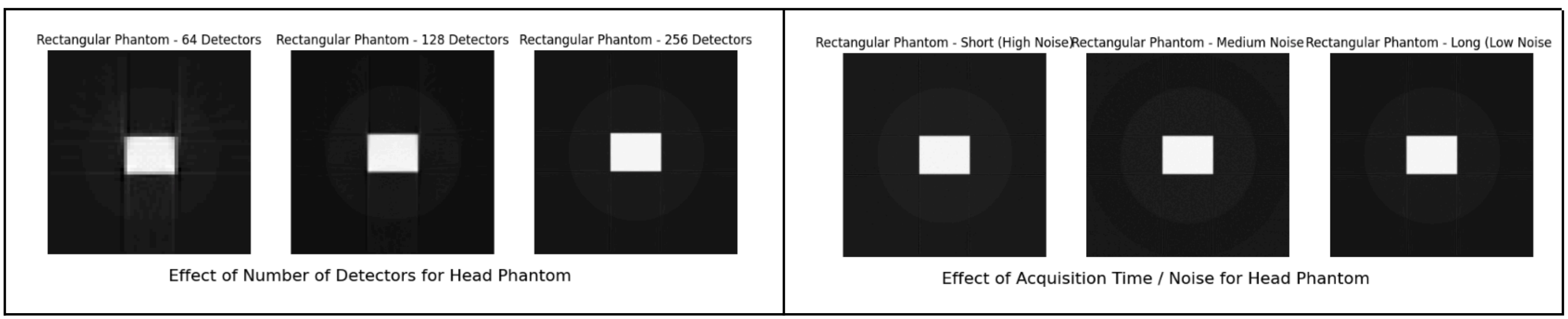
The SI profile shows that intensity values remain consistent between the original and reconstructed image, but transitions between the rectangle and background are less abrupt.

The difference image further emphasizes that reconstruction errors concentrate along edges and corners, where sharp gradient changes amplify sensitivity to noise and limited projections.

Quantitative metrics show structurally accurate reconstruction but with higher error values than the circular phantom, which is expected due to the rectangular phantom's non-smooth geometry.

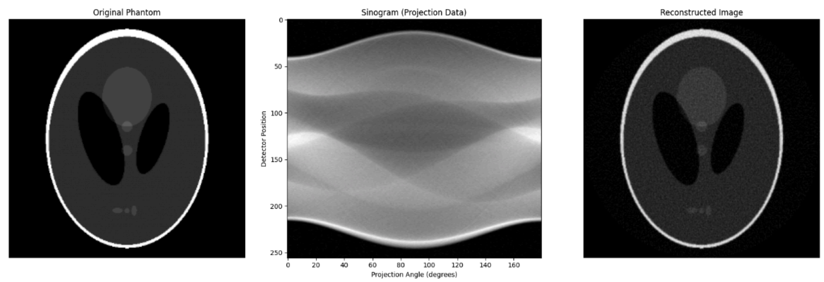
Overall, It confirms that the system accurately models attenuation but reveals how sharp edges naturally expose reconstruction limitations.





The acquisition parameter study demonstrates how the rectangular phantom responds to variations in projections, detector count, and acquisition time. With few projections, the edges become wavy and distorted due to incomplete angular sampling. Increasing projection count significantly sharpens the rectangular boundaries and reduces streak artifacts. Detector count also plays a major role: low detector density introduces jagged, stair-step edges, while higher density restores clean straight lines. Noise simulations show that longer acquisition times yield smoother reconstructions and more well-defined corners. These results confirm that the rectangular phantom is highly sensitive to sampling quality.

Head Phantom:

<table>
<tr>
<td>
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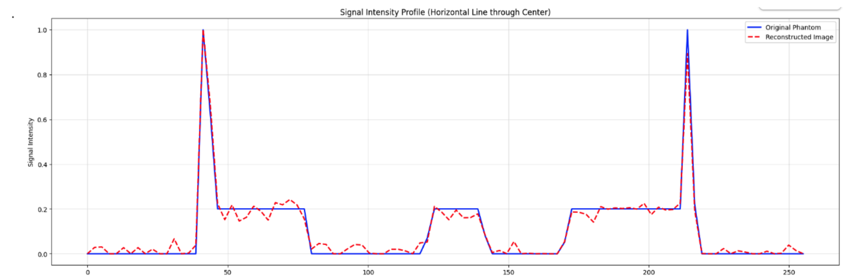
<td>
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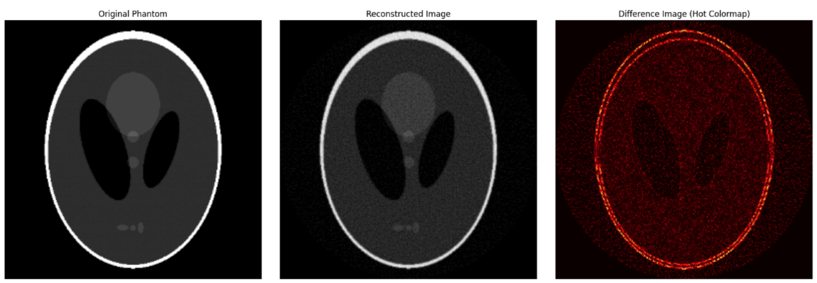
<td>
</td>
<td>A head phantom generated using the standard Shepp–Logan model, consisting of multiple ellipsoidal regions with different shapes and mu values that mimic anatomical soft-tissue and bone structures. Each component of the phantom was assigned a unique attenuation level to reproduce realistic contrast between tissue types. The code allows manipulating matrix size and scaling of attenuation values. This phantom provides a more complex and clinically relevant test case, enabling evaluation of the scanner’s ability to reconstruct layered, curved, and low-contrast structures found in real CT imaging.</td>
</tr>
</table>

Parameters	Analysis

```
======================================================================
                     ACQUISITION PARAMETERS USED
======================================================================
  Phantom Type:                   head
  Matrix Size:                    256 x 256 pixels
  Number of Projections:          180
  Step Angle (θ step):            1.000 degrees
  Number of Detectors:            256
  Detector Spacing:               1.000 pixels
  Source Distance:                384.0
  Detector Type:                  LINEAR
  Acquisition Time:               1.00 seconds
  Total Rotation Range:           180 degrees
  Noise Added:                    Yes
======================================================================
```

```
1. Signal Intensity (SI) and Contrast Analysis:
--------------------------------------------------
Original Phantom:
  Region 1 (Center) SI: 0.1078 ± 0.1279
  Region 2 (Background) SI: 0.2066 ± 0.0413
  Relative Contrast: 31.41%

Reconstructed Image:
  Region 1 (Center) SI: 0.1147 ± 0.1233
  Region 2 (Background) SI: 0.2069 ± 0.0506
  Relative Contrast: 28.65%

  Contrast Preservation: 91.2%
  (Used to verify beam attenuation is correctly calculated)

2. Image Difference Analysis:
--------------------------------------------------
  Mean Squared Error (MSE): 0.001365
  Root Mean Squared Error (RMSE): 0.036950
  Mean Absolute Error (MAE): 0.019754
  Structural Similarity Index (SSIM): 0.6248
```

The head phantom results in evaluating the scanner’s ability to reconstruct anatomically realistic structures with varying attenuation values.

The Shepp–Logan phantom includes soft tissue regions, higher-attenuation bone-like structures, and low-intensity interior components, making it a robust test object.

The sinogram shows complex overlapping projection patterns, confirming that all tissue layers were sampled across the full angular range.

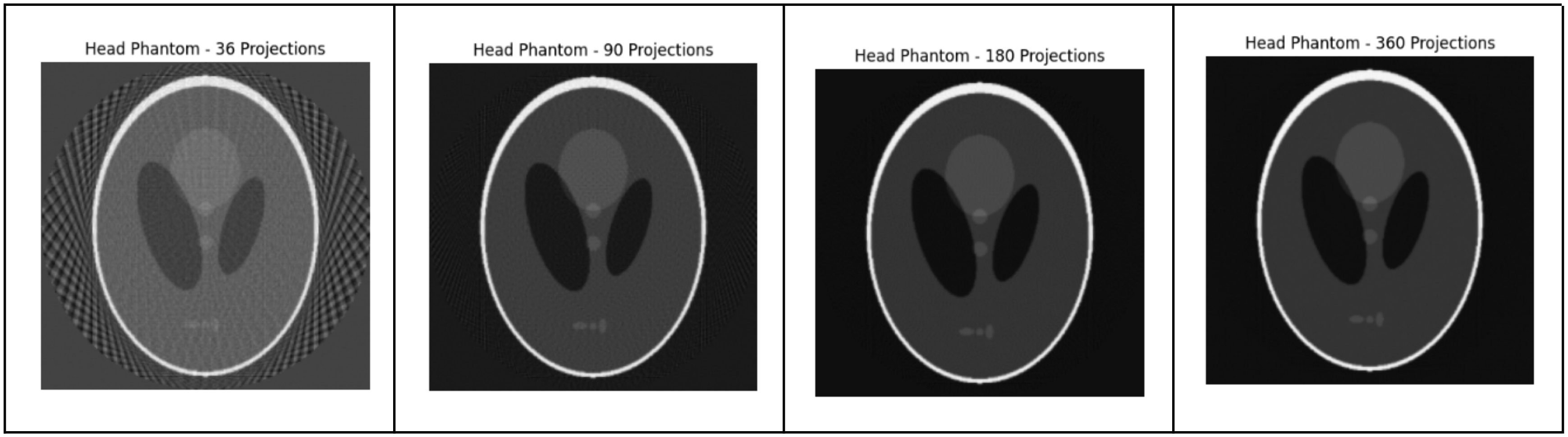
The reconstructed image preserves the major anatomical shapes, including the elliptical skull, inner cavities, and central ovoid regions.

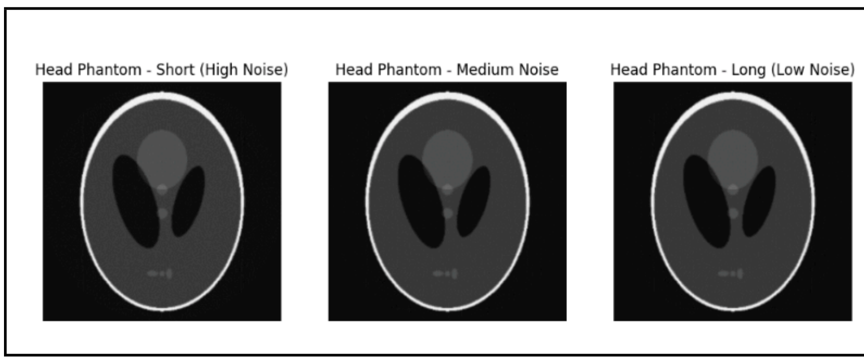
Some smoothing is visible in homogeneous areas, reflecting filter effects and noise handling. The SI profile reveals consistent intensity ordering across tissues, indicating proper attenuation modeling.

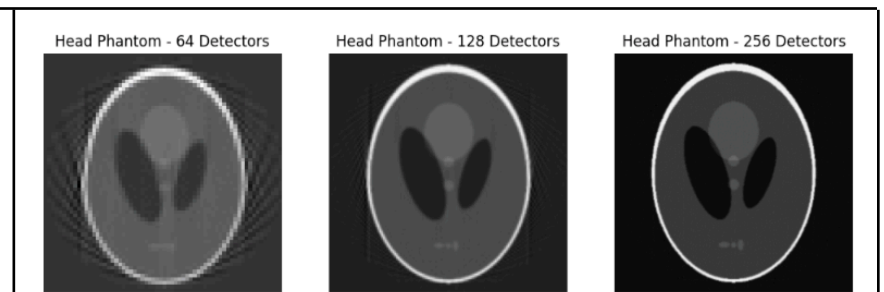
The difference image displays errors mainly along curved boundaries, where subtle gradients are more challenging to reconstruct accurately, and in low-contrast interior regions where noise has greater influence.

Error metrics confirm that structural similarity remains high while pixel-wise differences reflect natural reconstruction smoothing.

Overall, It demonstrates the scanner's capability to handle complex, nonuniform attenuation distributions typical of real CT imaging scenarios.







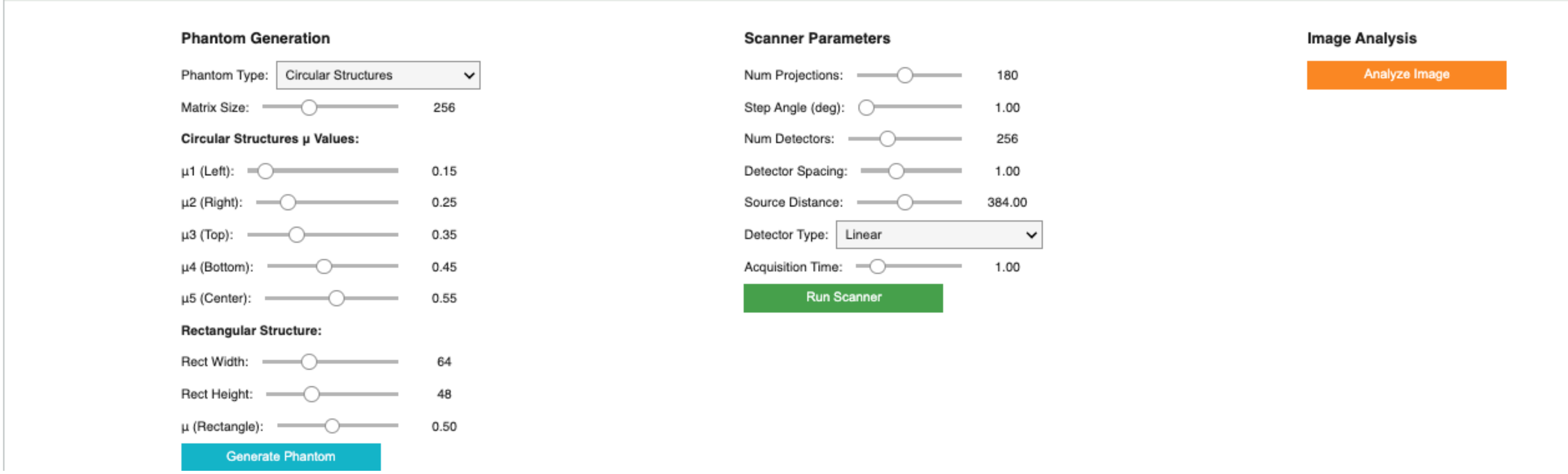
Effect of Acquisition Time / Noise for Circular Phantom

The acquisition parameter results show how the head phantom benefits from dense sampling and extended acquisition. With limited projections, anatomical boundaries blur and streak artifacts obscure internal structures. Increasing projection count greatly improves tissue contrast and reveals finer anatomical details. Detector count also influences clarity: more detectors enhance boundary smoothness and reduce pixelation along curved regions. Noise simulations indicate that longer acquisition times provide cleaner, less grainy results, making soft-tissue differentiation more reliable. These observations highlight the importance of adequate sampling for anatomically complex phantoms.

GUI Interface

```python
# Initialize the Virtual CT Scanner
ct_scanner = VirtualCTScanner()

# Display the GUI
ct_scanner.display_gui()
```



The GUI shown serves as an integrated control center for the virtual CT scanner, allowing users to perform phantom creation, data acquisition, reconstruction, and analysis within a single interactive environment. Users may select between the circular, rectangular, and head phantoms; adjust matrix size, structure dimensions, and attenuation values; and configure acquisition parameters such as detector count, spacing, rotation step, and total scan angle. The “Run” button executes the full scanning sequence and displays the phantom, sinogram, reconstructed image, difference image, and SI profile. The GUI also prints the acquisition parameters used, enabling users to track how adjustments influence reconstruction quality. This interface streamlines experimentation and reinforces conceptual understanding of CT imaging.

Conclusion

This project successfully demonstrates a full virtual CT scanner workflow, including phantom creation, projection acquisition, image reconstruction, and quantitative image analysis.

The circular, rectangular, and head phantoms each served different purposes in validating scanner performance. Circular structures confirmed baseline accuracy and contrast preservation, while the rectangular phantom highlighted edge-related artifacts and sampling sensitivity.

The head phantom tested the system under more realistic anatomical conditions, showing how reconstruction algorithms respond to complex attenuation patterns.

Across all phantoms, the sinograms, reconstructed images, difference maps, and signal-intensity profiles verified that the scanner behaved as expected. The acquisition parameter experiments further showed how projection count, detector density, and acquisition time influence reconstruction quality. Finally, the GUI allowed all tasks to be performed interactively, mirroring the workflow of a real CT system. Overall, the project meets all objectives and provides a complete educational platform for understanding CT image formation.