

# Column Laminography: A Phantom Simulation Study for 2D Vertical Cross-Sectional Imaging of a Distillation Column.

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## ABSTRACT

Distillation columns require continuous monitoring to maintain optimal performance, yet conventional gamma-ray column scanning provides only one-dimensional (1D) attenuation profiles, limiting diagnostic capability. This study investigates gamma-ray laminography as an advanced non-destructive technique for reconstructing two-dimensional (2D) vertical cross-sectional images of column internals. Computer simulations were performed using three phantom model which are normal trays, a missing tray, and trays with localized density anomalies. Projection data were reconstructed using Simple Back Projection (SBP) and Filtered Back Projection (FBP) with Ramlak and Cosine filters. Results showed that SBP produced blurred images with artifacts, while FBP methods yielded clearer images with improved contrast; the cosine filter provided the highest image quality. Laminography successfully identified missing trays and localized anomalies that were indistinguishable in 1D profiles, highlighting its superior spatial resolution. These findings demonstrate the potential of gamma-ray laminography to enhance industrial column diagnostics as a complementary method to conventional column scanning, with future work focusing on experimental validation and real-time implementation.

**Keywords:** Gamma-ray laminography, Distillation column diagnostics, 2D Image reconstruction

## 1. Introduction

Distillation columns are critical units in chemical and petrochemical industries, where their efficient operation is essential for product quality and energy consumption. Monitoring the internal conditions of distillation columns, such as liquid distribution, foaming, flooding, and tray damage, is crucial for maintaining optimal performance. Traditional inspection methods, such as shutdown inspections or intrusive probes, are costly, time-consuming, and disruptive to production. To address these challenges, non-invasive column scanning techniques have been developed, offering real-time insights into column performance without the need for shutdowns [1, 2].

Column gamma-ray scanning techniques provide a valuable means of assessing distillation column internals while the column remains operational [3]. These techniques involve a radiation source and detector traversing the column's exterior, measuring attenuation profiles that reflect internal density variations. The key advantages of column scanning include its non-destructive nature, non-intrusive operation, and the ability to perform online monitoring, allowing for immediate corrective actions. Despite these benefits, conventional column scanning produces only a one-dimensional (1D) profile plot, which offers limited information about the internal conditions. This profile does not provide detailed spatial resolution, making it difficult to distinguish between different types of flow anomalies or structural defects [4].

To overcome this limitation, a new approach called column laminography is proposed. This imaging technique complement the conventional column scanning technique by enabling two-dimensional (2D) vertical cross-sectional imaging. While traditional column scanning acquires data from a single source-detector pair at each level of interest, column laminography employs a single source position with multiple detector levels. Subsequently, collecting projection data that can be reconstructed into a 2D image through back-projection algorithms [5, 6]. This advancement allows for better visualization of internal column structures, such as tray liquid distribution, vapor flow patterns, and potential blockages, providing more comprehensive diagnostic capabilities.

In this study, a digital phantom simulation of column laminography is conducted to evaluate its feasibility for experimental application. This study extends our previous work, where radiation attenuation from the source to the detector through the column was simulated using the PHITS Monte Carlo package [7,8]. Unlike the earlier study, which focused on radiation transport and attenuation behavior, the present work emphasizes image reconstruction and

visualization. A computational model of a distillation column is developed, simulating different tray conditions, including normal operation, flooding, and damaged trays. Projection data are generated and reconstructed to assess the technique's ability to resolve internal features. The results will guide future experimental work by validating the reconstruction methodology and optimizing scanning parameters.

## 2. Methodology

### Fundamental of laminography scanning:

Column laminography scanning is performed to obtain a vertical cross-sectional image of a distillation column. Figure 1 illustrate the laminography scanning process. The scanning process begins by positioning a gamma-ray source and a detector facing each other at the topmost level of the column, denoted as position ( $S_1, D_1$ ). At this position, the attenuation of the gamma-ray beam is recorded. The detector is then descended in discrete steps to positions  $D_2, D_3, \dots, D_n$ , respectively, while the source remains fixed at  $S_1$ . At each detector position, the transmitted radiation is measured, completing the first projection profile.

For the second projection, the gamma-ray source is moved down to the next level ( $S_2$ ), and the same process of scanning from  $D_1$  to  $D_n$  is repeated. This stepwise procedure continues until the source has traversed from the top to the bottom of the column ( $S_1$  to  $S_n$ ), with a full set of projections collected at each level. These measured attenuation values form a projection dataset, which is organized into a sinogram or projection image representing the variation in density across the column's vertical plane. In practical industrial applications, this process is often implemented using a single source-detector pair due to physical and logistical constraints, though an array of detectors could be used in ideal scenarios to reduce scanning time.

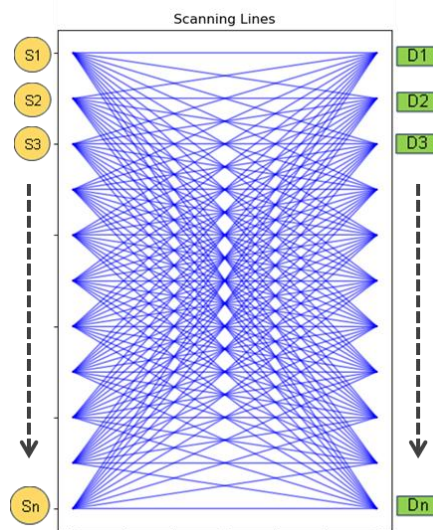


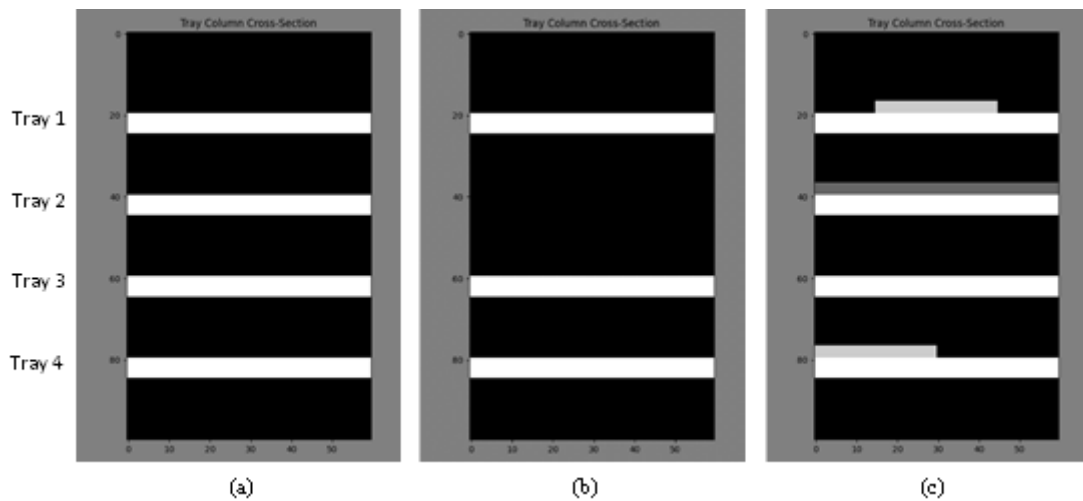
Figure 1. Fundamental of laminography scanning process

In this study, the entire scanning process is simulated computationally using a digital phantom of a tray column. As a result, projection data for all source positions ( $S_1$  to  $S_n$ ) are generated simultaneously without mechanical movement. The collected projections are then used to reconstruct the vertical cross-sectional image of the column using image reconstruction techniques. Two reconstruction methods are employed: Simple Back Projection (SBP) and Filtered Back Projection (FBP). The reconstructed images are compared and analyzed to evaluate their effectiveness in resolving internal tray conditions, such as normal operation, flooding, and structural damage. It should be noted that several simplifications are made in this digital phantom simulation. The model assumes idealized geometry, uniform material composition, and neglects certain radiation transport effects such as scattering, beam hardening, and detector noise. These assumptions allow computational efficiency and focus on evaluating reconstruction methodology, but they may limit the direct representativeness of the simulation to real experimental conditions. Future experimental validation is therefore essential to confirm the applicability of the proposed approach under realistic conditions.

### Phantom setup:

In this study, three different internal conditions of a distillation column are simulated using digital phantom models to evaluate the effectiveness of the proposed laminography technique. These conditions include: (1) a normal column with all intact trays, (2) a column with a missing tray that represents the mechanical failure, and (3) a column with abnormal tray conditions which mimics process-related anomalies. The phantoms are modeled as two-dimensional cross-

sectional images, with varying pixel intensities corresponding to different material densities. High-density materials, such as trays, are represented by white horizontal lines, while low-density regions such as air are shown as black background pixels.



**Figure 2.** 4-tray column model, (a) Normal condition, (b) Missing tray, and (c) Abnormally condition

Figure 2a illustrates the normal condition, where four equally spaced trays are installed inside the column. Each tray appears as a distinct white horizontal layer against the black background, indicating maximum attenuation due to the tray material. In Figure 2b, a mechanical failure is simulated by removing the second tray from the top, represented by the absence of the corresponding white layer. This condition mimics a physically missing or collapsed tray within the column structure.

Figure 2c presents the third scenario, where abnormal density distributions are introduced at the top regions of trays 1, 2, and 4. These abnormalities are modeled with varying gray pixel intensities to represent different material densities, such as liquid accumulation or deposits. The anomalies on trays 1 and 4 are modeled at 80 % of the tray's original intensity, while the anomaly on tray 2 is set at 40 % gradient. The anomalies on trays 1 and 4 are equal in size but different in position, whereas the anomaly on tray 2 extends fully across the tray's width. For consistency, the height of all three anomalies is identical. These three phantom models serve as test cases for assessing the accuracy and resolution of the image reconstruction algorithms in identifying both structural and operational faults within the column subsequently.

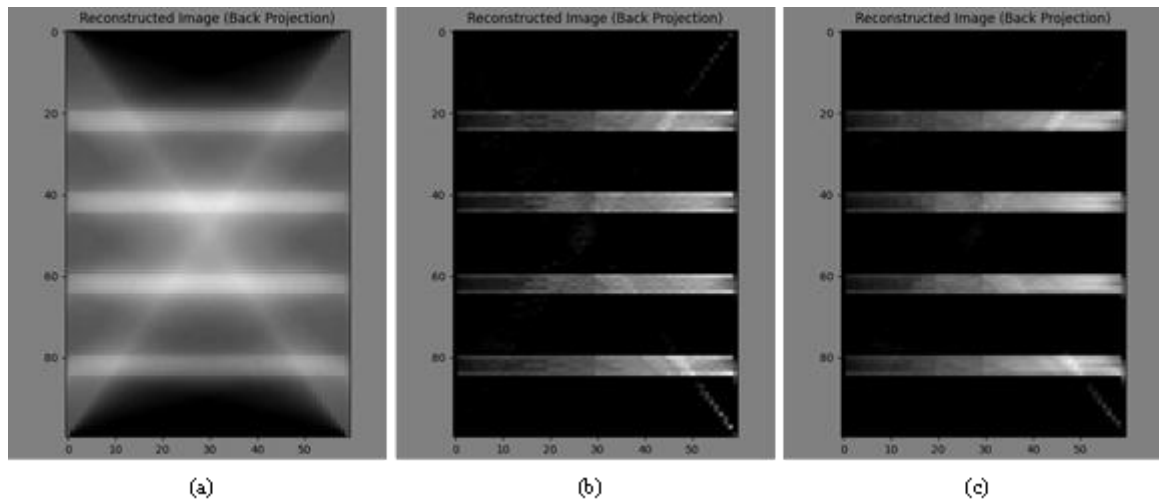
### 3. Results and Discussion

Three main highlights can be observed in this work. Firstly, comparing reconstruction method, secondly, assessing the internal conditions of the column and finally, comparison between 1D and 2D image reconstruction.

First, we focus on the computer simulation of laminographic scanning for a tray column, comparing three reconstruction methods: Simple Back Projection (SBP), Filtered Back Projection (FBP) with a Ramlak filter, and FBP with a cosine filter. Figure 3 presents the reconstructed images of the same normal tray condition using these methods. Figure 3(a) shows the reconstruction using SBP, Figure 3(b) using FBP with the Ramlak filter, and Figure 3(c) using FBP with the cosine filter. All three methods successfully reconstruct the trays in their correct positions, confirming the ability of each technique to capture the essential structural features of the column.

However, the SBP reconstruction in Figure 3(a) appears noticeably blurred due to the absence of a filtering step. This blurring is accompanied by high-intensity noise forming an 'x'-shaped pattern, which is attributed to the higher sampling rate along certain projection angles. Such patterns are analogous to ring artifacts and aliasing effects commonly observed in computed tomography (CT) reconstructions. These artifacts reduce the visual clarity and make it harder to distinguish between the trays and the background.

In contrast, both FBP reconstructions in Figures 3(b) and 3(c), show significantly improved clarity, with the blurring artifacts are largely eliminated. While the 'x'-shaped artifacts are still faintly visible in both cases, the contrast between the trays and the background is notably higher compared to SBP. Between the two filters, the cosine filter produces the best overall image quality, yielding smoother tray edges and more uniform background intensity than the Ramlak filter. This suggests that, for laminographic imaging of tray columns, FBP with a cosine filter provides a better balance between artifact suppression and image sharpness.



**Figure 3.** Laminography image reconstruction for tray column model, (a) SBP, (b) FBP-Ramlak, and (c) FBP-Cosine

**Table 1:** Image Quality Metrics for Different Reconstruction Techniques

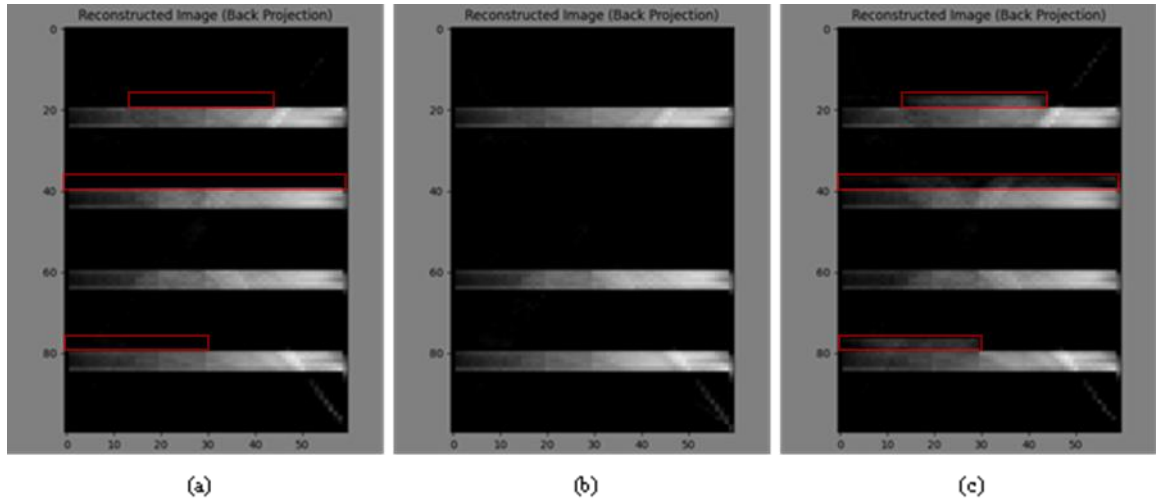
Reconstruction Algorithm	RMSE	PSNR	SSIM
SBP	39.17	8.14	0.20
FBP-Ramlak	27.44	11.23	0.72
FBP-Cosine	25.95	11.72	0.78

Table 1 shows the image quality metrics that compares the reconstruction performance of the three reconstruction algorithms used. The quality metrics calculated are Root Mean Square Error (RMSE), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM). The SBP method shows the poorest results with the highest RMSE (39.17), lowest PSNR (8.14 dB), and lowest SSIM (0.20), indicating high error, low signal quality, and poor structural similarity. The introduction of Ramlak filter significantly improves image quality, reducing RMSE to 27.45, increasing PSNR to 11.23 dB, and achieving an SSIM of 0.72. Further improvement is seen with the Cosine filter, which gives the lowest RMSE (25.95), highest PSNR (11.72 dB), and highest SSIM (0.78). This suggests that the Cosine filter provides a better balance between noise reduction and edge preservation. Overall, filtered back projection methods outperform simple back projection, with FBP-Cosine producing the most accurate and visually consistent reconstruction.

Next, the capability of laminography to image different internal conditions of the column is evaluated using the three phantom models. Figure 4 presents the reconstructed images of the normal tray condition, the missing tray condition, and the abnormal tray condition respectively, which are reconstructed using the FBP method with a cosine filter. Figure 4(a) shows the normal tray condition, which serves as the control case and corresponds to the phantom model described earlier. The red box highlights the region used for direct comparison with the abnormal tray condition shown in Figure 4(c).

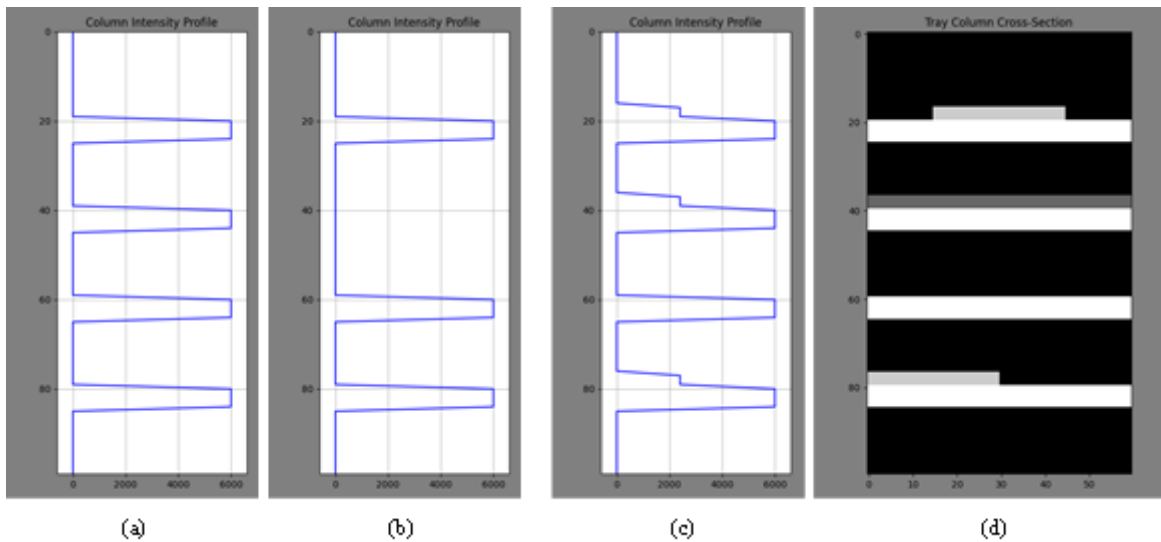
In Figure 4(b), the missing tray is clearly visible as the absence of a high-intensity horizontal line at the second tray position. This distinct gap confirms the ability of laminography to detect structural failures such as collapsed or absent trays. The clear visibility of the remaining trays, along with the uniform background, demonstrates that the FBP with cosine filter effectively preserves structural details while minimizing noise.

Figure 4(c) shows the reconstructed image of the abnormal tray condition, based on the phantom model described in Figure 2(c). The anomalies on trays 1, 2, and 4 respectively appear as additional high-density regions located at the upper portions of the trays, and are clearly visible within the red box indicators. The anomaly on tray 2, which extends fully across its width, is also distinctly identifiable. These results demonstrate that laminography with FBP and a cosine filter can effectively distinguish between normal, structurally damaged, and process-deviated tray conditions, providing valuable diagnostic information for operational monitoring.



**Figure 4.** Laminography image reconstruction for tray column model, (a) Normal tray, (b) Missing Tray, and (c) Abnormal tray conditions.

Finally, a comparison is made between the conventional column scanning method, which produces a one-dimensional (1D) profile plot, and the proposed laminographic scanning technique, which generates a two-dimensional (2D) reconstructed image. Figure 5 presents the results of the 1D profile plots for three different conditions: (a) the normal tray condition, (b) the missing tray condition, and (c) the abnormal tray condition, along with (d) the corresponding abnormal condition phantom used as a reference. In the plots, the x-axis represents the pixel count, which in practical column scanning corresponds to the gamma-ray attenuation measured at the detector. Higher pixel counts indicate greater attenuation, signifying the presence of high-density material at that scanning position, in this case, the trays.



**Figure 5.** Profile plot from conventional column scanning (a) Normal tray, (b) Missing Tray, and (c) Abnormal tray conditions and (d) Abnormal tray conditions phantom.

For the normal tray condition shown in Figure 5(a), the four distinct peaks appear at the expected positions, indicating no structural issues. Similarly, in Figure 5(b), the missing tray condition is evident as only three peaks are present, with the second tray level showing no peak, confirming the absence of material at that position. It should be noted that, in this simulation, the profile plots appear as clean, straight, square-wave-like signals because randomness and scattering effects of the gamma-ray source which commonly observed in real industrial scans are not included in the simulation.

The limitation of the 1D profile method becomes apparent in Figure 5(c), which corresponds to the abnormal tray condition. Although the anomalies on trays 1, 2, and 4 differ in density, size, and position, the profile plot shows them as identical peaks. This occurs because a 1D profile integrates the attenuation values across the entire x-axis of the scan, losing spatial information about the lateral position of the anomalies. For example, the anomaly on tray 2 has half the density but twice the size of the anomalies on trays 1 and 4 respectively; however, the integrated attenuation produces the

same peak height in the profile plot. Consequently, while 1D column scanning is sufficient for detecting missing trays or verifying the presence of trays, it is unable to distinguish between different lateral anomaly positions or variations in localized density thus, that limitations are compliment by the 2D imaging of laminography.

#### 4. Conclusions

This study demonstrated the feasibility of gamma-ray laminography as an advanced non-destructive technique for imaging the vertical cross-section of distillation column internals. Using computer-simulated phantom models representing normal, missing tray, and abnormal tray conditions, projection data were generated and reconstructed using Simple Back Projection (SBP) and Filtered Back Projection (FBP) with Ramlak and cosine filters. The results showed that while SBP could reconstruct the general tray structure, it produced blurred images with high-intensity artifacts. In contrast, both FBP methods yielded clearer images with improved contrast, with the cosine filter providing the best balance between image sharpness and artifact suppression. Quantitative evaluation further supports this observation, where FBP-Cosine achieved the lowest RMSE (25.95), highest PSNR (11.72 dB), and highest SSIM (0.78), indicating superior reconstruction fidelity and structural similarity compared to SBP and FBP-Ramlak.

The application of laminography to the missing tray and abnormal tray models confirmed its capability to detect both structural and process-related faults. Missing trays were clearly identified as the absence of high-density features at the expected positions, while localized anomalies of varying size, position, and density were distinguishable in the reconstructed images. This level of diagnostic detail cannot be achieved using conventional one-dimensional (1D) column scanning, which integrates attenuation along the scan axis and therefore loses spatial information.

Overall, the findings highlight the potential of gamma-ray laminography to significantly enhance the diagnostic capabilities of column scanning in industrial applications. By providing detailed two-dimensional (2D) images, laminography enables more accurate identification of structural defects and process anomalies without requiring column shutdowns. Future work will focus on experimental validation, optimization of scanning parameters, and the development of faster image reconstruction algorithms to enable practical deployment in real-time column monitoring.

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