Postprint: BLT Equation-Based Investigation of Aperture and Seam Coupling Effects on Shielding Effectiveness in Multilayer Shields

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Date: 2025-02-12T00:00:00+00:00

Abstract

Addressing the technical challenges of aperture coupling in multi-layer shielding enclosures, this study investigates the impact of aperture coupling on shielding effectiveness to provide technical support for the electromagnetic compatibility design of large radio telescopes. Based on the Robinson model and electromagnetic topology theory, equivalent circuits and signal flow graphs for double-layer apertured shielding cavities were established, shielding effectiveness was calculated using BLT (Baum-Liu-Tesch) equations, and the case of triple-layer cavities was also considered. A comparative analysis of measured values, simulated values, the Robinson algorithm, and the BLT algorithm was conducted to verify the accuracy of the BLT algorithm. Building upon this, the effects of layer spacing, aperture shape, and radiation source installation position on the shielding effectiveness of double-layer metallic cavities were analyzed in the 0–1.5;GHz frequency band, and engineering recommendations were proposed. Furthermore, the relationship between the number of layers and shielding effectiveness in triple-layer shielding cavities was analyzed, revealing a linear relationship between shielding effectiveness and layer count.

Full Text

Analysis of Factors Influencing the Shielding Effectiveness of Multi-layer Cavity Based on BLT Equation

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Abstract

This paper addresses the technical challenge of aperture coupling in multi-layer shielding cavities and investigates its impact on shielding effectiveness to provide technical support for electromagnetic compatibility design in large radio telescopes. Based on the Robinson model and electromagnetic topology theory, we establish an equivalent circuit and signal flow diagram for a double-layer perforated shielding cavity, solving for shielding effectiveness using the BLT (Baum-Liu-Tesch) equation while also considering three-layer cavity configurations. Through comparative analysis of measured values, simulation results, the Robinson algorithm, and our BLT algorithm, we verify the accuracy of the BLT approach. Building on this foundation, we analyze how layer spacing, aperture shape, and radiation source position affect the shielding effectiveness of double-layer metal cavities in the 0–1.5 GHz frequency band, offering practical engineering recommendations. Additionally, we examine the relationship between the number of layers and shielding effectiveness in three-layer shielding cavities, revealing a linear correlation between shielding effectiveness and layer count.

Keywords: telescopes: radio, methods: shielding effectiveness calculation, techniques: electromagnetic compatibility

1. Introduction

The Xinjiang Qitai 110 m Radio Telescope (QTT) currently under construction features extremely high sensitivity and an exceptionally low signal-to-noise ratio, making it vulnerable to electromagnetic interference from electronic equipment both inside and outside the observation site, which can compromise the accuracy of observational data [1-3]. To ensure a favorable electromagnetic environment for the radio telescope, electromagnetic compatibility issues for various types of equipment must be considered from the initial design stage, employing shielding techniques to suppress radiated interference from electronic devices that could affect astronomical observations. While single-layer metal shielding represents the most widely adopted solution, it often fails to meet the stringent electromagnetic compatibility requirements of radio telescopes. Consequently, multi-layer electromagnetic shielding schemes have gained increasing prominence in radio astronomy applications. For instance, the feed cabin of the world' s largest radio telescope FAST (Five-hundred-meter Aperture Spherical radio Telescope) utilizes a double-layer shielding method combining a stainless steel shielding main body with shielding cloth to reduce electromagnetic interference [4]. The Parkes 64 m radio telescope in Australia employs a multi-layer shielding scheme combining shielded cabinets and shielding boxes to suppress electromagnetic interference generated by ultra-wideband receiver terminals operating in the 0.7–4 GHz range. The QTT currently under construction also plans to adopt a multi-layer electromagnetic shielding scheme to mitigate interference with astronomical observations [1]. However, in practical engineering applications, metal shielding cabinets and boxes inevitably contain apertures and seams to accommodate ventilation, heat dissipation, cabling, and installation requirements. Electromagnetic signals couple through these apertures to the exterior of the shielding structure, ultimately affecting the shielding effectiveness. Therefore, investigating the influence of aperture coupling on the shielding effectiveness of multi-layer shielding structures is essential.

The analysis of shielding effectiveness (SE) for perforated shielding cavities has long been a research focus in electromagnetic protection. Current analysis methods fall into three categories: experimental, numerical, and analytical approaches. Experimental methods provide the most realistic and intuitive analysis of shielding effectiveness but suffer from high costs, time-consuming processes, difficult-to-meet test conditions, and poor repeatability [5]. Numerical methods primarily include the Method of Moments [6], Transmission-Line Matrix Method (TLM) [7], and Finite-Difference Time-Domain method [8]. While numerical methods offer high computational accuracy, they consume substantial computer resources and require long computation times. Analytical methods mainly comprise small-hole diffraction theory [9] and equivalent transmission line methods [10]. The equivalent transmission line method transforms electric field problems into circuit problems, offering clear physical meaning, simplicity, and high efficiency for analyzing how different parameters affect the results.

Building upon Robinson' s equivalent circuit method, previous studies [10–13] have investigated single-layer cavities from various perspectives including aperture position, aperture arrays, higher-order modes, and oblique plane wave incidence, all achieving high computational accuracy. However, after transforming electric field problems into circuit problems, Robinson' s algorithm only considers unidirectional electromagnetic field coupling when calculating equivalent voltages at each node, neglecting reverse voltage waves and consequently introducing certain errors. These errors become more pronounced when studying double-layer shielding cavities [14], as the additional calculation node leads to larger error accumulation. To account for bidirectional electromagnetic field coupling, Zhao et al. [15] built upon Robinson' s model [10] and employed electromagnetic topology theory and BLT equations to decompose the model into multiple independent subsystems. They introduced transmission pipelines to connect subsystems for energy transfer, then established correlation matrices between independent systems based on energy flow direction, comprising transmission and scattering matrices. This method solves for the shielding effectiveness of apertured cavities by establishing signal flow diagrams, treating apertures as two-port network nodes and using scattering matrices to account for the coupling effect of internal electromagnetic fields through apertures, yielding more accurate solutions. Da et al. [16] analyzed the influence of aperture number and area on shielding effectiveness using BLT equations, achieving results that not only closely matched simulation outcomes but also effectively estimated the resonant frequencies of shielding enclosures. Luo et al. [17] extended

BLT equations based on waveguide theory, proposing a method for rapidly and accurately calculating shielding effectiveness at arbitrary points within double-layer cavities. Wang et al. [14] investigated the effects of relative aperture positions and layer spacing on shielding effectiveness. Zhang et al. [18] summarized the influence of aperture position and quantity on double-layer cavity shielding effectiveness. Existing literature primarily focuses on single or double-layer shielding structures with certain algorithmic limitations; moreover, while three-layer shielding schemes are required in engineering applications, relevant research remains scarce.

In summary, this paper addresses the technical challenge that single-layer electromagnetic shielding cannot meet the electromagnetic compatibility control requirements of large radio telescopes. We propose using the Robinson model and electromagnetic topology theory to establish BLT equations for analyzing the impact of multi-layer shielding cavity aperture coupling on shielding effectiveness. The research findings provide theoretical support for the design of multi-layer electromagnetic shielding structures for QTT and hold significant engineering application value.

2.1 Establishment of Double-Layer Shielding Equivalent Circuit

[Figure 1: see original paper] illustrates a double-layer rectangular cavity with apertures irradiated by a plane wave. Using point O as the origin, a spatial rectangular coordinate system is established along the x, y, and z directions. The outer cavity near the excitation source has dimensions a × b × d_1, while the inner cavity measures a × b × d_2, with wall thickness t. Both inner and outer cavities have rectangular apertures of dimensions l_1 × w_1 and l_2 × w_2 respectively, located at the center of the left side. The excitation source is a plane wave with electric field E polarized perpendicular to the long side of the aperture. The electric field intensity monitoring point P is located on the center line of the inner cavity at a distance p from the inner aperture surface.

According to Robinson' s equivalent circuit theory, the cavity portion excluding the apertured surface is equivalent to a rectangular waveguide terminated by a short circuit. The plane wave is equivalent to voltage V_0. Free space is equivalent to a transmission line with characteristic impedance Z_0 and propagation constant k_0. T_1, T_2, and T_3 represent the two aperture nodes and the monitoring node, respectively. The apertures are equivalent to two admittances Y_1 and Y_2, while the admittance at monitoring point P is Y . The rectangular cavity is equivalent to a short-circuited waveguide with characteristic impedance Z_9 and propagation constant k_9, as shown in the equivalent circuit model in [Figure 2: see original paper].

In [Figure 2: see original paper], the voltage source V_0 represents the plane wave, with free-space wave impedance $Z_0 = 377\ \Omega$ and propagation constant $k_0 = 2\pi/\lambda$, where λ is the free-space wavelength. The impedance of a rectangular aperture is expressed as:

$jZ_0 \ \tan(2\pi l/\lambda)$

where

$Z_0 = 120\pi^2$ / [8w = w - 5t/4π (1 - (w /b)^2) (1 - (w /b)^2) + 4/(1 - 4/4πw) + ln(t)]

with l being the rectangular aperture length and w its width.

For TEmn modes propagating in a rectangular cavity, the characteristic impedance and propagation constant are respectively:

$k_9 = k_0\sqrt{}[1 - (m\lambda/2a)^2 - (n\lambda/2b)^2]$

$Z_9 = Z_0 / \sqrt{}[1 - (m\lambda/2a)^2 - (n\lambda/2b)^2]$

where m and n represent propagation modes in the rectangular waveguide.

Additionally, shielding cavities possess inherent resonant frequencies related to their dimensions. Resonance phenomena can either enhance or attenuate electromagnetic fields within the cavity. The inherent resonant frequency of a rectangular shielding cavity is:

f , , $= 150\sqrt{}[(m/d)^2 + (n/a)^2 + (k/b)^2]$

where f , , is in MHz, and d, a, b are the shielding cavity' s length, width, and height in meters, respectively. The mode numbers m, n, k take natural numbers 0, 1, 2, ···, but cannot have two or three simultaneously equal to zero.

2.2.1 Solution for Double-Layer Shielding Effectiveness

Electromagnetic topology theory was first proposed by Baum in 1974, after which Baum, Liu, and Tesche jointly developed the BLT equation for analyzing electromagnetic interference problems [19]. The generalized BLT equation represents a milestone for solving complex electromagnetic system problems. The fundamental concept involves decomposing a system into independent subsystems, introducing transmission pipelines and nodes from electromagnetic topology to obtain the system' s energy flow diagram (where nodes represent independent subsystems and pipelines represent electromagnetic wave energy flow directions), and finally establishing transmission and scattering matrices between subsystems.

Based on electromagnetic topology theory, the surfaces containing the two apertures and the cross-section at electric field monitoring point P in the double-layer cavity can each be equivalent to a two-port network, enabling construction of a signal flow diagram for the equivalent model shown in [Figure 2: see original paper], as depicted in [Figure 3: see original paper]. Pipeline 1 in the signal flow represents free space, while pipelines 2, 3, and 4 represent rectangular waveguides. WS denotes the plane wave, J_1 represents the observation node outside the cavity, J_2 and J_3 represent the outer and inner aperture nodes, J_4 represents the observation node inside the cavity, and J_5 represents the cavity terminal node. V^{n} , and V , represent the incident and reflected voltage waves at node j on pipeline i, respectively.

The basic form of the BLT equation is:

$V = P \cdot V^{n} - V^{0}$
$V = S \cdot V^{n}$
$V = V + V^{n}$

where equation (5) is the transmission equation, (6) is the scattering equation, and (7) is the voltage equation. V^{n} and V are incident and reflected voltage wave vectors, P is the transmission matrix, S is the scattering matrix determined by reflection coefficients Γ at each node, and V^{0} is the excitation source vector, assumed to be $V^{0} = (1, 0, 0, 0, 0, 0)$.

First, from the signal flow diagram, the transmission coefficients in transmission matrix $P = diag(\gamma_1, \gamma_2, \gamma_3, \gamma_4)$ are:

$\gamma_1 = 2e\hat{}(jk_0l_0)$
$\gamma_3 = 2e\hat{}(jk_0l_0)$
$\gamma_2 = 2e\hat{}(jkgd_1)\ e\hat{}(jkgp)\ e\hat{}(jk(d_2\text{-}p))$
$\gamma_4 = 2e\hat{}(jk(d_2\text{-}p))$

Second, analyzing the signal flow diagram reveals that node 1 has reflection coefficient $\Gamma_1 = [0]$, node 4 produces no reflection ($\Gamma_4 = 0$), and node 5 is a terminal short-circuit point with total reflection ($\Gamma_5 = [-1]$).

Combining the circuit in [Figure 2: see original paper] and the signal flow diagram in [Figure 3: see original paper], the circuit equation for the inner aperture can be established as:

$V^{n}{}_{2,3} + V_{2,3} = V^{n}{}_{3,3} + V_{3,3}$
$V^{n}{}_{3,3} - V_{3,3} = (V^{n}{}_{2,3} + V_{2,3})Y_{2}$

According to scattering parameter definitions, the scattering parameter S_{11} for the inner aperture (node 3) is:

$S_{11} = V_{3,3} / V^{n}{}_{3,3} = (Y_{2} - 2Y_9) / (2Y_9 + Y_{2}) = S_{22}$

Thus, the reflection coefficient at node J_3 can be obtained, and similarly for node J_2:

$\Gamma_2 = (Y_0 - Y_9 - Y_{1}) / (Y_0 + Y_9 + Y_{1})$
$\Gamma_3 = (2Y_9 - Y_{2}) / (2Y_9 + Y_{2})$

where Y_0, Y_9, Y_{1}, and Y_{2} are the characteristic admittances of free space, rectangular waveguide, outer aperture, and inner aperture, respectively. Since admittance and impedance are reciprocals, they can be calculated using equations (1) and (3). The scattering matrix is therefore $S = diag(\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5)$.

Combining equations (5)–(7) yields the generalized voltage BLT equation:

$V = (E + S)(P - S)^{-1}V^0$

where E is the identity matrix. The voltage at node J_4 is $V_{6,1} + V_{7,1}$ in voltage vector V. For multiple propagation modes in rectangular waveguide, the total voltage at observation point J_4 is:

$V \quad = \Sigma|V \, , |$

The shielding effectiveness is then calculated using:

$SE = 20\log_{10}(V' \quad / V \,)$

where V' is the voltage at the cavity center line without shielding. This allows calculation of shielding effectiveness at any point P on the center line of the inner cavity.

2.2.2 Solution for Three-Layer Shielding Effectiveness

Based on the description in Section 2.2.1, the three-layer shielding model differs from the double-layer model by adding one node in the solution process. Following the double-layer model' s naming convention, the cavity lengths from left to right are d_1, d_2, and d_3, where d_3 is the inner cavity length. The transmission and scattering matrices for the three-layer BLT equation are:

$P = diag(\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5)$
$S = diag(\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5, \Gamma_6)$

$\gamma_1 = 2e\hat{}(jk_0l_0)$
$\gamma_3 = 2e\hat{}(jkgd_2)$
$\gamma_2 = 2e\hat{}(jkgd_1)$
$\gamma_4 = 2e\hat{}(jkgp)\ e\hat{}(jk(d_3\text{-}p))$
$\gamma_5 = 2e\hat{}(jk(d_3\text{-}p))$

$\Gamma_1 = 0$
$\Gamma_2 = (Y_0 - Y_9 - Y_{\ 1}) / (Y_0 + Y_9 + Y_{\ 1})$
$\Gamma_3 = (2Y_9 - Y_{\ 2}) / (2Y_9 + Y_{\ 2})$
$\Gamma_4 = (2Y_9 - Y_{\ 3}) / (2Y_9 + Y_{\ 3})$
$\Gamma_5 = -1$
$\Gamma_6 = -1$

Finally, using equations (11)-(13), the shielding effectiveness at any point on the center line of the three-layer shielding cavity can be calculated.

2.3 Algorithm Validation

To verify the validity and accuracy of the BLT method, a validation model was established. The double-layer shielding cavity with a single rectangular aperture has an outer cavity length $d_1 = 20$ mm and inner cavity length $d_2 = 300$ mm, with both inner and outer apertures measuring 100 mm × 10 mm. To ensure resonant consistency, all cavity models in this study have inner dimensions of a × b × d = 300 mm × 120 mm × 300 mm, are made of aluminum with 1 mm wall thickness, consider only the dominant TE_{10} mode, and operate in the frequency range of 0–1.5 GHz. Unless otherwise specified, test antennas are positioned at the center of the inner cavity by default.

[Figure 4: see original paper] shows the double-layer shielding box made of aluminum plate. Following the GB/T 12190 standard for shielding effectiveness measurement [21], its shielding effectiveness was measured. Due to antenna test frequency limitations, measurements were taken from 300 MHz to 1.5 GHz at 100 MHz intervals, with additional frequency points at 707 MHz, 750 MHz, and 1.15 GHz to capture resonances. During testing, the receiving antenna was placed at the center of the shielding box interior, while the transmitting antenna was positioned two meters away at the same height. The shielding effectiveness value was determined as the difference between signal strength received without the shielding structure and that with the shielding structure in place. The calculated results were compared with traditional Robinson equivalent circuit algorithm, TLM numerical algorithm, and measurement results.

The theoretical and experimental results are shown in [Figure 5: see original paper]. The shielding effectiveness calculated by all three algorithms shows consistent overall trends with measurement results, with our algorithm demonstrating high agreement with TLM numerical method and measured data. Since Robinson' s model does not consider the coupling effect of internal electromagnetic fields to the exterior, while the BLT equation incorporates incident and reflected voltages at each node and connects the entire system through scattering and transmission matrices, the BLT method achieves higher accuracy than traditional equivalent circuit methods, with calculation errors of approximately 10 dB, consistent with conclusions in reference [14]. All three algorithms predict three resonant points (f_{110}, f_{210}, f_{111}) within the considered frequency range. As only fundamental mode transmission is considered in this study, calculation accuracy decreases at higher frequencies. [Figure 5: see original paper] also shows an anomalous increase in shielding effectiveness at 500 MHz for the BLT method, which occurs because the waveguide characteristic impedance in equation (3) is mistakenly considered infinite for TE_{10} mode; this has no practical impact and will be ignored and avoided in subsequent analysis.

The comparative experimental results demonstrate that the BLT method exhibits good performance in predicting double-layer cavity shielding effectiveness with high computational accuracy. Therefore, compared with Robinson' s equivalent transmission line method, it offers greater reliability for analyzing multi-layer shielding structures. Since this model exhibits only a few resonant points in the 0–1.5 GHz frequency range, subsequent studies on shielding effectiveness influencing factors will continue using this model to avoid resonance effects and facilitate pattern identification.

3 Analysis of Influencing Factors on Double-Layer Cavity Shielding Effectiveness

Considering that double-layer shielding schemes are more widely applied in engineering practice, this section focuses on double-layer shielding cavities. Three primary factors are considered in actual double-layer shielding design: the distance between outer and inner enclosures, aperture shape (as shielding structures often require various aperture shapes and sizes), and the installation position of radiation sources or sensitive equipment within the shielding box. This study investigates these three factors and their influence on double-layer cavity shielding effectiveness.

3.1 Influence of Layer Spacing on Shielding Effectiveness For the double-layer cavity shown in [Figure 1: see original paper], the inner cavity dimensions remain constant while the outer cavity length d_1 is set to 20 mm, 60 mm, and 80 mm. Monitoring point P is located at the inner cavity center with coordinates (150, 60, 150), and the frequency range is 0–1.5 GHz. The calculation results for layer spacing effects are shown in [Figure 6: see original paper]. At frequencies below 900 MHz, the shielding effectiveness at the inner cavity center increases with outer cavity length, though the improvement magnitude decreases. Above the second resonant frequency, shielding effectiveness does not follow this pattern, prompting further continuous analysis of layer spacing at typical frequency points.

The shielding cavity can be regarded as a rectangular waveguide. [Figure 7: see original paper] shows shielding effectiveness versus outer cavity length at typical frequencies. Based on waveguide theory, the cutoff frequency is 500 MHz. Electromagnetic waves below cutoff frequency (400 MHz) attenuate rapidly in the waveguide, with attenuation increasing with distance. Near cutoff frequency (501 MHz), shielding effectiveness remains essentially constant with increasing distance. Electromagnetic waves above cutoff frequency (530 MHz, 900 MHz) can propagate through the waveguide, and shielding effectiveness exhibits periodic behavior, meaning its value depends on layer spacing magnitude. Comparing results at 530 MHz and 900 MHz reveals that higher frequencies produce shorter periods, with variation amplitudes reaching approximately 40 dB. These results indicate that shielding effectiveness becomes more difficult to calculate at high frequencies, as small position changes significantly impact shielding performance.

Therefore, larger layer spacing is not always better. Below the cavity cutoff frequency, shielding effectiveness increases with layer spacing. Above cutoff frequency, shielding effectiveness shows periodic variation with layer spacing, with higher frequencies producing shorter periods. In practical engineering applications, layer spacing can be selected based on this periodic variation. For example, when interference signals at both 530 MHz and 900 MHz are present simultaneously, [Figure 7: see original paper] shows that setting the outer cavity length to 0.3 m or 0.5 m yields higher shielding effectiveness.

3.2 Influence of Aperture Shape on Shielding Effectiveness In engineering applications, rectangular apertures often have different aspect ratios, making it necessary to analyze how aperture shape affects shielding effectiveness. Based on the double-layer shielding model in [Figure 1: see original paper] and maintaining constant aperture area, aperture dimensions are set to l × w = 100 mm × 5 mm, 50 mm × 10 mm, and 25 mm × 20 mm, with identical aperture sizes in both inner and outer cavities centered on the cavity walls. Other settings remain unchanged from the previous section. Calculation results for different dimensions are shown in [Figure 8: see original paper]. As the aspect ratio decreases, shielding effectiveness at the inner cavity center increases significantly, with improvements reaching 40 dB. Additionally, at 1.2 GHz, both resonance bandwidth and intensity decrease. [Figure 9: see original paper] shows shielding effectiveness versus rectangular aperture long-side length, with the minimum length being 500 mm (square aperture). At a given frequency, shielding effectiveness is negatively correlated with rectangular aperture length, with square apertures being more advantageous for improving shielding effectiveness and suppressing resonances.

Reference [22] indicates that for the same area, circular apertures provide 3–5 dB higher shielding effectiveness than square apertures. In summary, for practical applications with constant ventilation area, square or circular apertures should be prioritized over rectangular ones, avoiding elongated shapes.

3.3 Influence of Radiation Source Installation Position on Shielding Effectiveness The electromagnetic field distribution within a shielding cavity is non-uniform, meaning shielding effectiveness varies at different positions inside the cavity, which provides guidance for installing interference radiation sources. Based on the double-layer shielding model in [Figure 1: see original paper], the monitoring point position parameter p is varied to values of 100 mm, 150 mm, and 200 mm, with other conditions unchanged. Calculation results are shown in [Figure 10: see original paper]. Below the first resonant frequency (707 MHz), shielding effectiveness increases with distance from the aperture. The three positions exhibit essentially the same resonant frequencies, but at p = 100 mm, resonance also occurs at 900 MHz, causing a sudden decrease in electric field intensity and creating a shielding effectiveness peak.

[Figure 11: see original paper] shows shielding effectiveness versus observation distance at different frequencies. At p = 100 mm, the curve bulges at 900 MHz, indicating resonance, consistent with the phenomenon in [Figure 10: see original paper]. The results show that regardless of frequency, shielding effectiveness at p = 300 mm is infinite, as this model can be considered a short-circuited waveguide. Using the terminal as a reference, shielding effectiveness exhibits periodic variation as p decreases, with amplitude changes of approximately 40-60 dB and a period equal to half the guided wavelength [23]. In this model, for electromagnetic waves at 900 MHz, the guided wavelength is approximately 400 mm, producing a shielding effectiveness peak at p = 100 mm. As frequency increases, the variation period shortens.

In summary, at low frequencies, shielding effectiveness is lower closer to the aperture. At high frequencies, shielding effectiveness does not continuously increase as the radiation source moves away from the aperture but instead shows periodic variation, starting from the cavity terminal (the point of maximum shielding effectiveness) with a period equal to half the wavelength of electromagnetic waves in the rectangular waveguide. Based on these results, in engineering applications, radiation sources should be installed at the shielding box terminal or at distances from the terminal equal to integer multiples of half the wavelength of electromagnetic waves at the interference frequency within the cavity. For example, when the interference frequency is 1.2 GHz, [Figure 11: see original paper] shows that sensitive equipment or radiation sources placed at positions 0.025 m, 0.16 m, or 0.3 m from the aperture yield maximum shielding effectiveness and minimal interference with radio astronomical observations.

4 Relationship Between Number of Layers and Shielding Effectiveness

Existing shielding engineering applications for large radio telescopes require ultra-high-performance electromagnetic protection, creating demand for three-layer shielding schemes. It is necessary to analyze the relationship between shielding effectiveness and layer count in three-layer shielding structures.

To analyze the response relationship between layer count and shielding effectiveness in multi-layer shielding cavities, the structure in [Figure 1: see original paper] was extended leftward into a three-layer configuration, with the first and second cavity lengths both set to 20 mm and other conditions unchanged. [Figure 12: see original paper] presents shielding effectiveness calculation results for one, two, and three layers. To verify BLT algorithm accuracy for three-layer configurations, TLM simulation and Robinson model results were included, demonstrating that the BLT method maintains high accuracy for three-layer shielding. The results clearly show that increasing layer count significantly improves shielding effectiveness.

[Figure 13: see original paper] shows shielding effectiveness versus layer count at three frequency points: 400 MHz, 900 MHz, and 1.3 GHz. The results indicate an approximately linear relationship between shielding effectiveness and layer count. Below the second resonant frequency (400 MHz, 900 MHz), each additional layer increases shielding effectiveness by 14–16 dB. At 1.3 GHz, the average increase per layer decreases to approximately 9 dB. The incremental error between layers 1$→2*and*2→$3 does not exceed 1 dB across all three frequencies.

Based on these results, for multi-layer shielding structures with apertures, shielding effectiveness has a linear rather than simple multiplicative relationship with layer count. Multi-layer shielding schemes can thus mitigate interference with radio astronomical observations, but evaluation must recognize that multi-layer shielding effectiveness is not simply a multiple of single-layer performance.

5 Conclusion

This study addresses the ultra-high-performance electromagnetic protection requirements of large radio telescopes by investigating the impact of apertures on shielding effectiveness in multi-layer metal cavities. Using equivalent circuit and electromagnetic topology theories, we implemented BLT equations to analyze how multi-layer shielding cavity apertures affect shielding effectiveness, validating the approach through numerical and experimental methods. Based on a practical example, we analyzed the influence of layer spacing, aperture shape, and radiation source position on double-layer cavity shielding effectiveness in the 0–1.5 GHz range, and investigated the relationship between layer count and shielding effectiveness in three-layer cavities. The results demonstrate that among the three influencing factors, radiation source installation position most significantly affects shielding effectiveness. In practical engineering, equipment must be installed at optimal positions within shielding boxes based on theoretical predictions. Furthermore, multi-layer cavity shielding effectiveness exhibits a linear relationship with layer count rather than a simple multiplicative one, providing theoretical support for evaluating QTT multi-layer shielding schemes.

Future research should address the heterogeneity, randomness, and complexity of multi-layer electromagnetic shielding structures in engineering applications, strengthening the combination of theory and measurement while further investigating seam effects in multi-layer shielding cavities.

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Note: Figure translations are in progress. See original paper for figures.