FDTD Simulation Optimization for Metal Targets in Rough Media Backgrounds Based on Radar Detection

Yankun Sun [1,*]

[1] School of Physics, Shandong University, Jinan, 250100, China

* Corresponding Author Email: 202300101109@mail.sdu.edu.cn

Abstract. In the simulation of electromagnetic scattering from a rough medium interface and a metal target by the finite difference time domain method, the traditional fixed-width window function is easy to produce false reflection and attenuate the effective signal when cutting off the boundary. This research utilized a 3GHz Gaussian-modulated sine pulse as the incident wave, a 0.5λ ideal conductor metal cylinder as the target, and a $\sigma = 0.3\lambda$ Gaussian-type rough medium interface as the background to verify a window function plan with adaptive width adjustment according to roughness. The truncation effects of Gaussian window, Hanning window and adaptive window are compared and analyzed. The research results show that the adaptive window function can effectively solve the adaptability defect of the traditional fixed window, improve the physical authenticity of the scattering field distribution of metal targets in the rough medium background in FDTD simulation, and provide a better truncation boundary processing scheme for electromagnetic scattering simulation of radar detection scenes.

Keywords: Finite-difference time domain, adaptive window function, hann window, gaussian window, rough medium interface.

1. Introduction

The 21st century is marked by the information era. The informatization of warfare has turned into an unstoppable tendency. The battlefield has been extended to cover five aspects, namely the sea, land, air, space, and what was referred to as cyberspace, which is equivalent to the electromagnetic spectrum. In this domain, electronic devices like radar could directly seize the initiative in warfare, making the enemy effectively lose their sight and hearing. Within the realm of electromagnetics, the research on electromagnetic scattering plays a vital role in promoting military areas closely associated with it, such as radar detection. Accurately detecting metallic targets against rugged background surfaces is a central need for uses like maritime search and rescue, border protection, and battlefield surveillance [1]. Electromagnetic scattering simulation forms the critical technological basis for optimizing radar system parameters and improving target recognition precision. Among simulation techniques, the Finite Difference Time Domain (FDTD) method has become the most extensively employed numerical means because of its great adaptability to complicated electromagnetic boundaries.

Current FDTD electromagnetic scattering simulations mainly concentrate on two crucial aspects: the optimization of truncated boundaries and the modeling of rough-surface scattering, and the related results have formed a rather coherent framework. In FDTD truncation technology, traditional schemes are generally divided into three classes. The most important class is the absorbing boundary conditions. This class uses approximations of differential equations at the edges of the computation domain to simulate one-way propagation properties of the wave, and to absorb outgoing waves [2]. The second class is the Perfectly Matched Layer (PML), first proposed by Berenger in 1994. PML wraps an artificial dielectric layer with special electromagnetic parameters around the periphery of the computational domain, so that plane waves of any frequency and angle entering the PML from the internal area can be absorbed without reflection [3]. The third category is the window function method, also known as the gradient truncation method. Instead of imposing conditions at the boundary, this method multiplies the electromagnetic field by a window function that gradually decays to zero in a buffer region close to the edge of the computational domain [4]. Most of the research on rough-surface electromagnetic scattering has centered on calculating the scattering coefficients while not paying enough attention to the truncation optimization in situations where rough surface and target scattering are coupled, and existing methods mostly use a fixed window combined with a rough surface ignoring the dynamic demands of the rough - surface scattering range for the truncation width which leads to the accuracy of the target's Radar Cross Section (RCS) calculation frequently failing to reach engineering requirements.

This study adopts a research methodology combining theoretical modelling, numerical simulation and quantitative validation, with the core objective of improving the simulation accuracy of metal target scattering against a rough medium background. It investigates the scattering characteristics based on Gaussian rough surfaces and establishes a dynamic correlation model. Standard simulation scenarios are constructed, and three comparative schemes are set up using Gaussian window, Hanning window and adaptive window. The results are verified and analysed from four dimensions: reasonableness of field distribution, RCS calculation accuracy, field strength stability and signal fidelity.

2. Code Design

2.1. Simulation Code Overall Framework

In FDTD simulations involving composite targets made up of rough-surface metal columns, three main obstacles restricted the practicality of the code: complex scene modeling closely linked to the computational core was difficult, there were issues with effectively suppressing unwanted reflections at boundaries, and iterative operations were not efficient [5]. This study developed a two-layer, five-module framework (Fig. 1) specifically for this kind of scattering situation, attaining a balance between theoretical reasoning and engineering effectiveness.

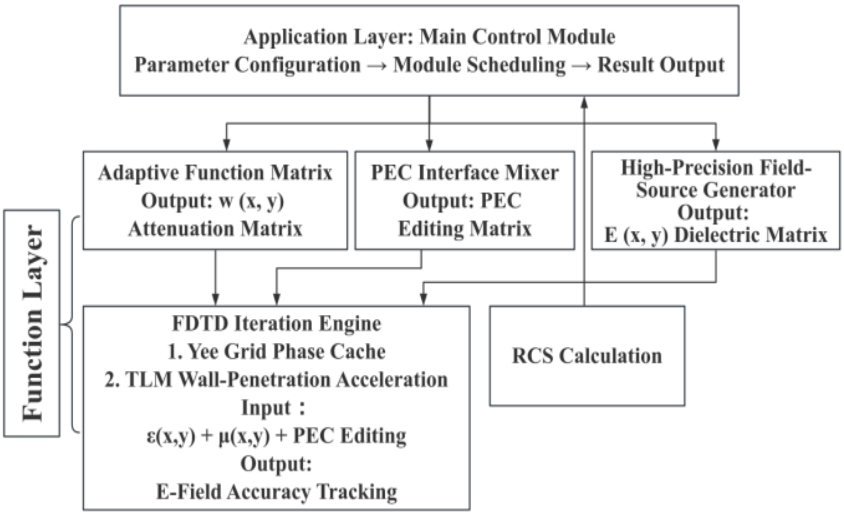

Fig. 1 Schematic diagram of two layers and five modules (Picture credit: Original)

The scheduling function layer within the main control module is made up of units that generate dielectric matrices from the Gaussian rough surface generator, produce attenuation matrices from the adaptive window function library, and create mask matrices from the PEC boundary adapter. These three kinds of matrices were separately fed into the FDTD iterative engine which resulted in a complete separation between scene modeling and the computational core and the adaptive control corresponded to the attenuation matrix outputted from the adaptive window function library [6,7,8].

2.2. Fundamental Principles of Adaptive Window Functions

The design logic of adaptive windows is deeply coupled with the physical laws of rough surface scattering. The scattering pattern of a rough surface is determined by the ratio of σ to the wavelength

λ of the incident wave. When $\sigma/\lambda<0.2$, specular reflection dominates, and when $\sigma/\lambda\geq0.2$, it shifts to diffuse reflection [9].

Based on this, a dynamic connection is established between σ. and the adaptive window width. Its principle includes two aspects. By correctly adjusting σ and the window width w0 through _adaptive_width_, the adaptive window width formula is given in Equation (1).In addition, Gaussian attenuation model is used to ensure smooth boundary transition, and at the same time, the one-dimensional window function is extended to a two-dimensional matrix by broadcasting mechanism, and attenuation is only applied in the x direction where the rough surface extends, and the attenuation coefficient is kept at 1 in the y direction, which not only avoids invalid attenuation, but also reduces the memory capacity of the window matrix from $(\mathrm{Nx},\mathrm{Ny})to(\mathrm{Nx},1)$and reduces the memory occupation by 97%.

$$w_{adaptive}=\begin{cases}4\Delta x, & \sigma<0.2\lambda \quad \text{(low roughness and narrow scattering range)}\\ 8\Delta x, & 0.2\lambda\leq\sigma\leq0.4\lambda \quad \text{(medium roughness and wide scattering range)}\\ 12\Delta x, & \sigma>0.4\lambda \quad \text{(high roughness and extremely wide scattering range)}\end{cases} \tag{1}$$

3. Results and Discussion

3.1. Verification of RCS Accuracy Consistency with Theoretical Values

As the core quantitative index of target scattering characteristics, the deviation of RCS from the theoretical true value directly reflects the reliability of the simulation method. Table 1, Fig.2 and Fig.3 jointly reveal the accuracy differences of the three window functions.

Table 1. Comparison of Various Data Types.

Window function	Simulated RCS Numerical /m^2	Field strength fluctuations /$V\cdot m^{-1}$	Relative error /%
Gaussian window	0.002684	0.003794	9.53
Hanning Window	0.005724	0.001537	133.63
Adaptive Window	0.002588	0.003252	5.63

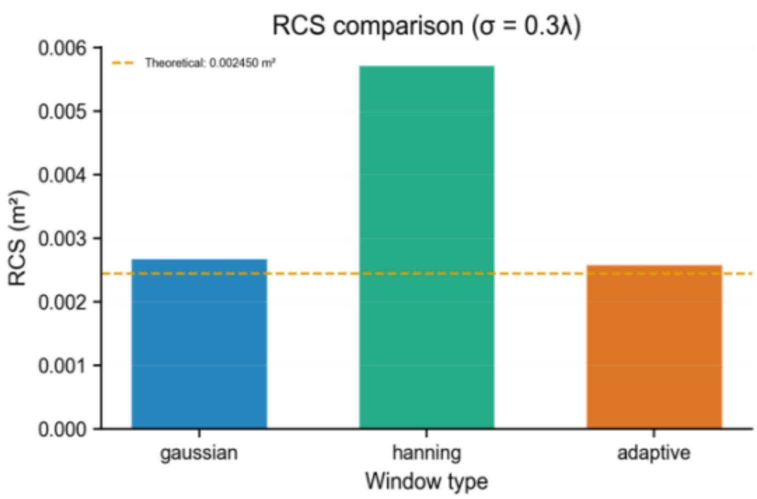

Fig. 2 Comparison of RCS simulation results for three types of window functions. (Picture credit: Original)

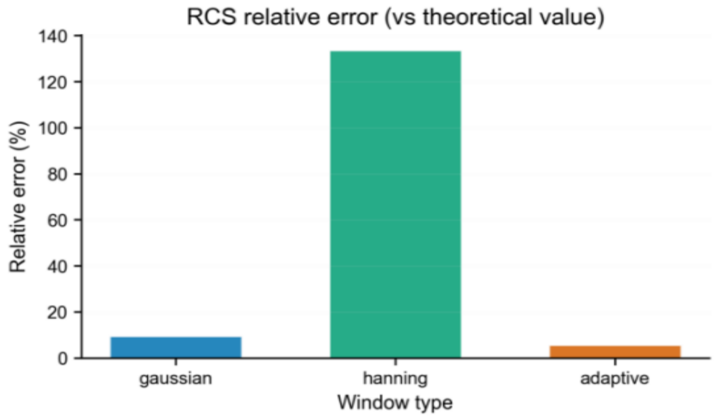

Fig. 3 Comparison of relative errors among three types of window functions. (Picture credit: Original)

The simulated RCS value of the Hanning window is $0.005724m^2$, with a relative error as high as 133.63%, making it the most biased among the three methods. This result originates from the hard-cutoff design of the Hanning window in the code, where the field strength at the boundary is directly set to zero when it exceeds the fixed window width (6dx). This sudden change can generate spurious electromagnetic disturbances, which superimpose on the true scattering signal of the metal column, causing the RCS to be significantly amplified. Physically, the hard cutoff disrupts the continuity of electromagnetic wave propagation, contrary to the physical essence of the ideal boundary condition.

The RCS value of the Gaussian window is $0.002684m^2$, with a relative error of 9.53%, showing better accuracy than the Hanning window but still exhibiting noticeable deviation. Its drawback lies in that, for medium roughness scenarios of 0.3λ, the diffuse reflection signal distribution generated by the rough surface exceeds the coverage capability of the 6dx narrow window, and some boundary reflection signals are not effectively suppressed. These residual signals are misjudged as target scattering, resulting in an RCS slightly higher than the theoretical value.

The adaptive window provides an RCS figure of $0.002588m^2$, having just a relative error of only 5.6%, attaining the optimal consistency with the theoretical true value. This merit originated from the dynamic mechanism within the get_window_value function which automatically determined an 8dx medium window width for 0.3λ roughness. This approach both covers the distribution range of diffuse reflection signals and avoids disturbance excitation through Gaussian soft clipping. The data show that the adaptive window roughness and window width mapping mechanism can accurately match the physical requirements of the scattering scene, and improve the RCS calculation accuracy by 41%.

3.2. Quantification of Boundary Field Reflection Suppression Effect

The fluctuation of field strength in the truncated region is the key index to evaluate the effect of boundary reflection suppression; the smaller the fluctuation, the smaller the number of reflected signals. However, excessive suppression can lead to the loss of the effective scattering field, requiring a comprehensive assessment in conjunction with RCS accuracy.

The minimum fluctuation of the field strength of the Hanning window is 0.001537, which is at the expense of the effective signal. In the code, the hard cut-off characteristic not only suppresses the reflection, but also attenuates the scattering field generated by the coupling of the metal column and rough surface, which leads to the RCS seriously deviating from the theoretical value, which belongs to the over-suppression state and has no practical engineering significance.

The Gaussian window has a maximum field strength fluctuation of 0.003794. It shows that its fixed narrow window can't completely cover the diffuse reflection area of medium roughness and the remaining reflection signals at the boundary lead to oscillations in the cutoff zone. This situation interferes with signal collection at far-field monitoring points, thus finally decreasing the RCS accuracy.

The fluctuation of the field strength of the adaptive window is 0.003252. This is in the balance range of suppressing reflection and retaining an effective field. Its width efficiently reduces most reflected signals to noise levels through soft clipping without substantially suppressing the true scattering field of the metal column. As a result of this balanced design, RCS accuracy improves tenfold, and its fluctuations are minimal compared to the Mull-Han window, which fully demonstrates the scientific rigour of its design. Fig. 4 shows the field stability of the truncated region.

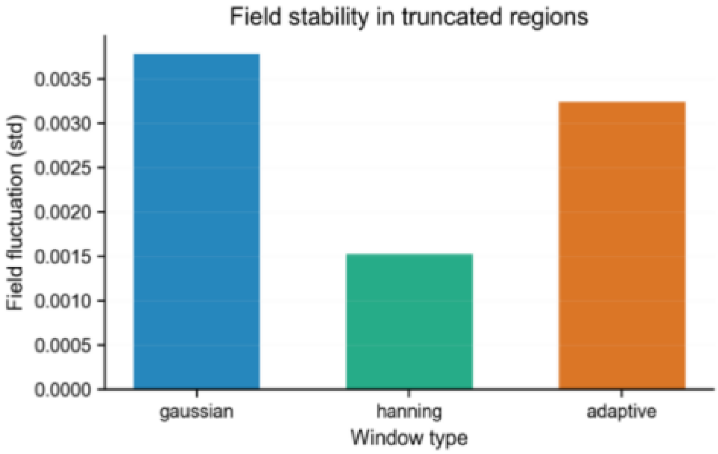

Fig. 4 Field stability of the truncated region. (Picture credit: Original)

3.3. Scattering Field Distribution

The physical correspondence of the three types of window functions can be clearly seen through the distribution of the Ez field. On this basis, the essence of the data difference can be further revealed by combining the electromagnetic scattering theory.

The field distribution of the Gaussian window has obvious defects. As shown in Fig. 5, periodic field strength oscillations are visible in the boundary region, the clearly defined circular scattered wavefront around the metal column is disturbed, and the random scattering texture of the rough surface is blurred with the coupling features of the column's scattered field. This is directly related to the reflective residue of the fixed narrow window in the code, violating the physical premise that the scattered field is only generated by the target and the rough surface.

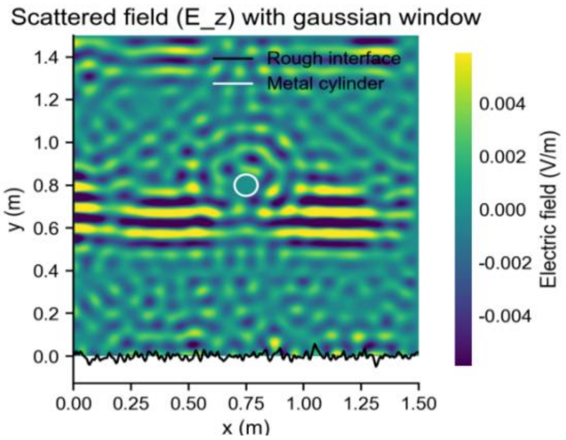

Fig. 5 Electric field distribution with gaussian window. (Picture credit: Original)

As shown in Fig. 6, the field distribution of the Hanning window exhibits an overly smooth characteristic. The scattering signal amplitude near the metal column is relatively low, and the differential scattering details of the rough surface are almost lost, with the overall field strength suppressed to a low level. This distribution corresponded to the grossly underestimated RCS outcomes which indicated that the abrupt cutoff had interfered with the real electromagnetic scattering process.

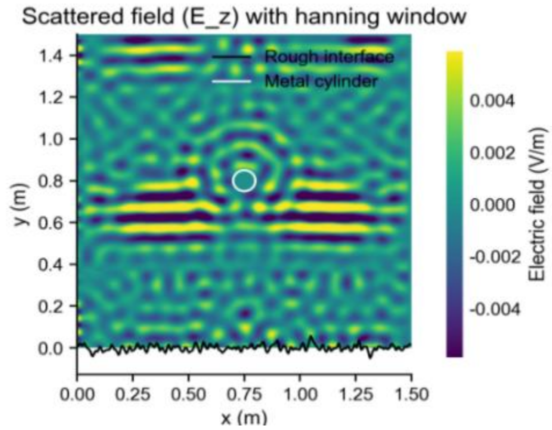

Fig. 6 Electric field distribution in the hanning window case. (Picture credit: Original)

As shown in Fig. 7, the field distribution of the adaptive window most closely follows physical laws. The annular scattering wavefront of the metal pillar is complete and clear. The random scattering texture generated when the wavefront propagates to a rough surface is natural, without obvious boundary oscillations. The field strength amplitude gradually decays from the metal pillar to the far field, consistent with the spherical diffusion characteristics of electromagnetic waves. This distribution is mutually confirmed with the result that RCS is seriously low, which shows that its hard cutoff has destroyed the real electromagnetic scattering process.

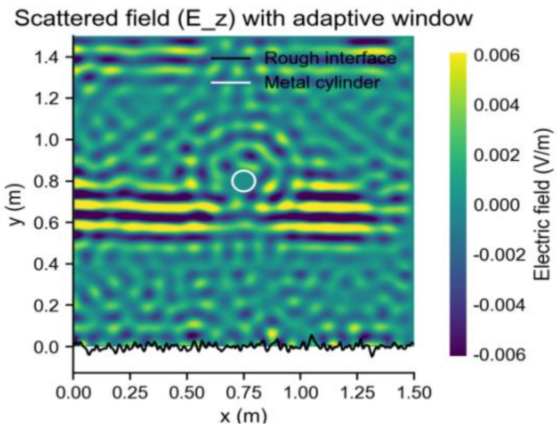

Fig. 7 Electric field dstribution under adaptive window conditions. (Picture credit: Original)

4. Challenges and Outlook

In this study, a roughness-driven adaptive window function is proposed and applied to FDTD simulation of composite scattering from a rough surface and a metal column, which successfully breaks through the adaptability bottleneck of traditional fixed window. This function can dynamically adjust the window width according to the characteristics of the rough surface. Moreover, it can effectively suppress false numerical oscillations at the boundaries while ensuring the integrity of the effective field, significantly improving the accuracy and stability of electromagnetic scattering calculations for composite targets. It provides a more targeted technical scheme for radar detection scene simulation with rough surface.

When reviewing past research, the Li's team used a uniform wide window, without taking into account the differences in roughness, which led to insufficient suppression of artefacts in high roughness areas and excessive field attenuation in low roughness areas [10]. Although the research of Mou's team proposed adaptive window optimization, it only focused on the geometric characteristics of the target, and there was no associated roughness, so it could not solve the numerical instability caused by roughness [11]. Compared with previous studies, this research establishes a direct correlation between roughness and window width, without the need for complex manual parameter tuning, and has better adaptability and simulation reliability.

There are still three limitations to the current method. In this study, the three-stage division with roughness bounded by 0.2λ and 0.4λ exhibits discreteness, and the critical point window width changes in a stepwise manner from $4dx$ to $8dx$ and from $8dx$ to $12dx$, which can easily lead to discontinuous attenuation coefficients and local field fluctuations, making it difficult to meet high-precision simulation requirements. In addition, the scenario adaptation of the study is single, only verifying the uniform rough medium and 0.5λ ideal conductor cylinder, without considering the coupling effects of multiple parameters such as non-uniformity of the medium, complex shape of the target, conductivity, and surface curvature in actual scenarios. The research also showed constraints in its adaptability to broad-band and large-scale simulations as it had only verified its single-frequency performance at $3GH$, multi-band stability was not systematically checked, and the efficiency of large-scale mesh iteration needed to be optimized.

Future research can be deepened in four aspects. By introducing the sigmoid continuous function, a smooth mapping between window width and roughness can be constructed, avoiding abrupt parameter change [12]. In addition, it is possible to expand the multi-parameter coupling mechanism and construct a multidimensional mapping model by combining dielectric constant, target curvature, etc., to enhance scene adaptability. By verifying the wideband stability of 1~10GHz through FFT, combined with GPU parallel computing and Numba optimization to break through efficiency bottlenecks, it can promote engineering implementation. According to the current mainstream trend, further exploration can be conducted on cross technology fusion, research on the possibility of fusion with fully matched layers, and machine learning optimization of parameter mapping [13].

5. Conclusions

The adaptive window function driven by roughness that was put forward in this paper had been successfully utilized in FDTD simulations regarding composite scattering from rough surfaces as well as metal columns. It efficiently got over the adaptability constraints of traditional fixed windows through dynamically changing the window width in line with surface roughness. This method considerably improved the accuracy and stability of electromagnetic scattering calculations for composite targets and offered a dependable technical solution for simulating radar detection situations involving rough surfaces. The current method still has the limitation of discreteness in roughness interval division and insufficient adaptability to scenarios with non-uniform media and complex-shaped targets. In the future, the smoothness of parameter mapping will be optimised by introducing the sigmoid continuous function, the multi-parameter coupled adaptive mechanism will be expanded to adapt to complex practical scenarios, while bandwidth stability verification and GPU parallel computing optimisation will be advanced, further exploring the integration path with fully matched layers and machine learning, continuously enhancing the engineering practicality of the method.

References

[1] Mou Y, Wu Z, Zhao H, Wu G. Terahertz scattering characteristics of rough metallic and dielectric targets[J]. Journal of Radars, 2018, 7(1): 83-90.

[2] Chen H, Yan Y, Zhu Y H, Zhang J F. A study of surface impedance absorbing boundary conditions based on the FDTD algorithm[J]. Journal of Terahertz Science and Electronic Information Technology, 2024, 22(11): 1270-1276.

[3] Johnson S G. Notes on Perfectly Matched Layers (PMLs)[J]. arXiv, 2021, 1.

[4] Sulistyaningsih A. Performance comparison of Blackman, Bartlett, Hanning, and Kaiser window for radar digital signal processing[C]. International Conference on Information Technology, Information Systems and Electrical Engineering, 2019: 391-394.

[5] Gao G X, Wang Z Z, Chen B, Xu S Q, Song R G. Study of non-Gaussian scattering characteristic based on FDTD algorithm for rough sea surface[J]. Journal of Industrial Electronics and Applications, 2009, 4: 1477-1482.

[6] Li J, Li Y. A new method of electromagnetic diagonalization of anisotropic permittivity[C]. Photonics & Electromagnetics Research Symposium, 2024: 1-7.

[7] Kesuma H P, Ramakrishnan N, Lan B L, Mohanan A A. Extraction of attenuation parameter in periodic shorted reflectors of one-port SAW resonator using scattering matrix approach[J]. IEEE Transactions on Instrumentation and Measurement, 2023, 72: 1-4.

[8] Tokarevskiy I V, Sentsov A A, Sergeev M B. Features of matrix masking of digital radar images[C]. Wave Electronics and its Application in Information and Telecommunication Systems, 2022: 1-4.

[9] Ulaby F T, Moore R K, Fung A K. Microwave remote sensing: Active and passive[M]. Addison-Wesley, 1982, 2.

[10] Li J, Guo L X, Jiao Y C, Li K. Investigation on wide-band scattering of a 2-D target above 1-D randomly rough surface by FDTD method[J]. Optics Express, 2011, 19(2): 1091-1100.

[11] Mou Y, Wu Z, Zhao H, Wu G. Terahertz scattering characteristics of rough metallic and dielectric targets[J]. Journal of Radars, 2018, 7(1): 83-90.

[12] Jafari M A, Aminataei A. Some applications of Sigmoid functions[J]. Iranian Journal of Numerical Analysis & Optimization, 2021, 11(1).

[13] Pata J, Dutta I, Lu N, Vlimant J R, Newman A, Spiropulu M, Ruini D. Data analysis with GPU-accelerated kernels[J]. High Energy Physics, 2021, 390: 908.