Research on computation and simulation technology of battlefield complex electromagnetic environment

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Abstract. In view of the current fierce competition for electromagnetic power among countries, it is necessary to accelerate the simulation of frequency equipment in complex electromagnetic environments, and to construct complex electromagnetic environment simulation scenarios under joint combat conditions. How to construct the complex electromagnetic environment that meets up with the requirement of battlefields, and to improve combat command and training capabilities are the current research problems. Thus, this paper studies the simulation and calculation of the complex electromagnetic environment in the battlefield, and proposes and designs a system for the calculation and analysis of the complex electromagnetic environment of battlefield. The system can be used to estimate radio wave propagation of each frequency equipment, to analyse and compute complex electromagnetic situation of the battlefield, and visualize them. The above estimation, analysis, and computation are obtained according to the displacement of frequency equipment, and battlefield environment, such as geography information and meteorological information. The proposed system can obtain the impact of electromagnetic environment of the battlefield on various types of frequency equipment, and provide battlefield electromagnetic information protection for equipment application.

1. Introduction
In previous wars, the US military used various means of electronic interference, and radar equipment, etc. for investigations and counter-reconnaissance, interference and anti-interference, and anti-radiation destruction [1,2], to quickly won absolute victory of the war. Currently, U.S. military concerns a lot about the performance evaluation of frequency equipment in complex electromagnetic environments [2]. The main methods include the construction of complex electromagnetic environments, recording, analysis and monitoring of test parameters, attention to the leakage of electromagnetic parameters and participation in actual equipment, and the use of real electronic devices and a large number of simulators to generate complex electromagnetic environments, and using interactive simulation techniques to construct complex electromagnetic environments [3]. For the future war, information is the key factor that restricts the victory of the war. The frequency equipment of future battlefield is highly intensive, and the electromagnetic environment is extremely complex. Constructing a complex electromagnetic simulation environment that meets the requirements of battlefield joint operations and equipment performance standards, and making troops and informational equipment to training and practicing during such a simulation environment can improve combat capabilities, which also a practical action of actual battle-warning. This paper studies the calculation and simulation of the complex electromagnetic environment in the battlefield, and proposes and designs a system for the calculation and analysis of the complex electromagnetic environment on the battlefield. The system can be used to estimate radio wave propagation of each

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frequency equipment, to analyse and compute complex electromagnetic situation of the battlefield, and visualize them. The above estimation, analysis, and computation are according to the displacement of frequency equipment, and according to battlefield environment, such as geography information and meteorological information. The proposed system can obtain the impact of electromagnetic environment of the battlefield on various types of frequency equipment, and provide battlefield electromagnetic information protection for equipment application.

2. Related Work

2.1. Electromagnetic Situation Computation

Currently, for the calculation of electromagnetic situation [4], some studies are limited to the calculation of the electromagnetic situation of a single frequency equipment [3]. The calculation of the electromagnetic situation of the entire battlefield can be very complicated. The early calculation method is slow. When a large number of stations involved in the calculation, the requirement on calculation speed is very important. As shown in Fig. 1, when calculating the electromagnetic situation in a certain area, it is necessary to calculate the electromagnetic field intensity generated by multiple stations at each point in 3D space [5]. As the 3D space is relatively large, the amount of data after grid division is very large. Every relevant station participating in the calculation must undergo such a large number of calculations, which will greatly reduce the operating speed of the system and seriously affect the availability of the system. It is necessary to study new methods for calculating the electromagnetic situation of space, which is accurate and having faster computational efficiency.

![Fig.1 Three-Dimensional Electromagnetic Computation Complexity Schematic](image)

According to the above model, there is still a problem that the calculation time is too long. Especially in practical applications, hundreds of stations are often analysed at the same time, and the calculation speed is difficult to meet the requirements. If we only calculate electromagnetic environment data within 30 km of four provinces (assuming the area is 500 × 500 km² for each province), this algorithm will calculate the synthetic field strength of nearly 30 million points on the ground and in space, and average calculation time at each point is about 6 seconds (assuming there are 2,000 stations in the area), even if just doing a rough calculation (assuming a point of 1,000 meters), the time required for preliminary estimation is: \((500+500) \times (500+500) \times 30 \times 6S \)/(3600S/H×24H/D×30D/M×12M/Y) ≈5.8Y, where S is short for second, H is short for hour, D is short for day, M is short for month, and Y is short for year. It takes almost 6 years, and the entire calculation time is simply unbearable. Therefore, this algorithm is only suitable for the analysis and calculation of small-area and small number of stations. It is necessary to study new algorithms and methods, to improve the speed of analysis and calculation.

2.2. Wave propagation prediction

The propagation modes [6] involved in the whole frequency band mainly include waveguide mode propagation, ground wave propagation, sky wave propagation (ionospheric reflection propagation), free space propagation, spatial wave propagation, barrier diffraction propagation, smooth ground diffraction propagation, and Tropospheric scatter propagation, etc. The establishment of corresponding forecasting methods for the above propagation modes is a key point to carry out simulation research.
The wave propagation analysis [7,8] is the core technology of the battlefield electromagnetic situation analysis and display. The basic content is to pre-analyse and calculate the electromagnetic field intensity distribution in a 2D and 3D space of a combat area based on station equipment data and geographic information data, to form electromagnetic situation. Electromagnetic situation information can be further used to display and frequency equipment impact analysis. The basic idea of the radio wave propagation analysis and calculation is to calculate space electromagnetic field coverage generated by stations according to station's location, power, antenna directionality, frequency, etc., and combine the geographical information on the propagation path, with the radio wave propagation model that is suitable for the local area and suitable for the corresponding frequency band. By analysing and calculating all stations in this region, the electromagnetic field distribution data at each spatial point and at each frequency can be obtained. These data can be used to analyse and display the electromagnetic situation of the battlefield.

3. System design and key techniques

3.1. System design

The proposed system has constructed a set of equipment test simulation software platform integrating experimental planning, whole-process electromagnetic numerical simulation analysis, 2D and 3D visualized deduction and comprehensive evaluation. It can carry out equipment test training mission planning, confrontation quantitative analysis of equipment testing and training, equipment test training confrontation deduction, equipment testing training comprehensive assessment, regional background situation analysis, point spectrum analysis, frequency equipment range of action analysis, equipment model management, shown as Fig.2.

![Battlefield Complex Electromagnetic Environment Calculation and Analysis System Diagram](image)

**Fig.2** Battlefield Complex Electromagnetic Environment Calculation and Analysis System Diagram

1. **Electromagnetic situation analysis:** Electromagnetic environment analysis mainly includes analysis of frequency range of equipment, radar power area analysis, regional background analysis, point spectrum analysis.

2. **Mission planning and visualization:** The system equipment models are divided into mobile platform equipment and frequency equipment. User deploys different equipment models in the desired combat space, sets the operational parameters of the equipment and meteorological regions, and constructs a specific battlefield electromagnetic environment. The functions of mission planning include the deployment of frequency equipment, the deployment of mobile platform platforms, the scheduling of platform operations, etc.

3. **Comprehensive assessment of data:** Evaluate the effective interference counted by the both confrontation parties, and compare them according to the degree of interference (mild, moderate, and severe).
And the database includes various models and data supporting the system's operation, including Geography information database, Frequency Equipment Model database, Radio propagation model database, Electromagnetic Situation Database, and Visual Simulation Model database.

3.2. Contributions

The main contributions of the system are to address the problems of lacking of quantitative calculations and information supporting methods in experimental training. The proposed system highlights the application of simulation calculations, and constructs a set of equipment simulation systems for electromagnetic environmental information. The system integrates the whole process of numerical simulation calculation, visualized deduction, and comprehensive evaluation. It pays attention to calculation of battlefield environment model, interactive revision of role parameters, and results evaluation of human-in-the-loop, and intensifies the training of command skills based on information technology. The following 2 contributions are proposed:

3.2.1. Electromagnetic situation calculation algorithm

The computation of electromagnetic situation space data requires comprehensive consideration of equipment technical data, antennas, geographic information data, and a variety of possible propagation mechanisms. The process is extremely complex, and the amount of calculation is large, and with the number of frequency equipment increases, the amount of calculation rapidly increases. Thus, this paper studies and solves the rapid matching calculation technology that matches with antenna models and terrain features, the electromagnetic situation raster technology, dynamic refresh, rapid request and extraction, and situational synthesis technologies. This paper also implemented rapid analysis and calculation of the electromagnetic situation, which provides strong support for the visualization of the electromagnetic situation. This paper has studied the calculation method of electromagnetic situation from different aspects and achieved good results, shown as following:

(1) Electromagnetic Situation Grading. In order to increase the speed of calculation, this paper has adopted a functional hierarchy. The functions of different levels correspond to the needs of different levels. Correspondingly, calculations with different degrees of accuracy are used to increase the speed of calculation. The specific measures are as follows:

(a) Functional classification. The electromagnetic situation is divided into overall situation, regional situation, and single-station situation according to the ranges of calculation. The overall situation focuses on area larger than 500 km². Other situational analysis focuses on area less than 500 km². The overall electromagnetic state function can help user understand the basic electromagnetic situation of the entire combat area.

(b) Optimization of overall electromagnetic situation. The purpose of the overall electromagnetic situation is to provide users with a macroscopic electromagnetic situation. Its characteristic is that the area of calculation and the number of stations are large, and the requirements on local details are not very high. The calculation method can be greatly simplified to improve the calculation speed.

(c) Optimization of regional electromagnetic situation. What we concerned most is the distribution of local electromagnetic environment within the region, so we need a more detailed analysis and calculation. This paper has adopted the following methods to improve the accuracy and speed of the system.

- Select a relative small area for analysis and calculation to reduce the amount of computation.
- Meshing. According to the experiments on the algorithm, combined with the research results and experience of relevant units, this paper sets the grid of the regional situation to 100-1000 meters.
- For data management, situation data is saved as volume data for those stations that are participated in the regional situation analysis. If the volume data already exists in the next calculation and the station parameters do not change, then the existing data is used directly. In this way, as the number of calculations increases, the system will be faster and faster.
The analysis of a single electromagnetic situation adopts the most elaborate analysis method. Because the analysis of a single station, even if the highest accuracy is selected, the calculation time is acceptable. The optimization of a single station calculation is mainly from the aspect of data management, storing the situation volume data of a single station, and combined with the operation of the database. As long as the parameters of the station remain unchanged, its volume data is saved without repeating calculations. In this way, many key stations can be calculated and stored in advance.

(2) Algorithm of automatic fast matching between radio service and antenna pattern. Antenna patterns used by different communication services have different characteristics. The antenna of the earth station generally has a certain elevation angle and the directional pattern is relatively sharp. The directional pattern of the alert radar antenna is generally relatively sharp in order to accurately determine the position of the target. And the fixed service, especially the fixed service of the microwave frequency band, is required to obtain a better result. High gain antenna patterns are usually sharp; broadcast services use non-directional or wide-directional antennas in order to achieve a large coverage area. Therefore, the antenna pattern should match its service. In actual calculation process, when the data of the actual antenna pattern is missing, the error is large. The system must establish a spatial three-dimensional antenna pattern based on the minimum information such as the antenna gain, so as to establish a 3D spatial distribution of field strength and display 3D electromagnetic situation. The establishment of matching antenna pattern models for various communication services is also a challenge for the system. The electromagnetic situation analysis and display system includes almost all radio communication services. Thus, we have established a technique for matching antenna patterns with radio services for the application of this system. This technique has two advantages:

(a) Solved the problem of missing antenna pattern data in the equipment database. In the database design of this system, a special antenna data table is designed, which includes the description of the antenna directional data. However, in the data collection process, this data is difficult to collect, resulting in a large number of device antennas have no direction data. The accuracy of the calculation cannot be guaranteed. Using the proposed method, it supports for the calculation of equipment without this data, and the accuracy of the calculation is guaranteed.

(b) Increased calculation speed. When we choose to automatically match the antenna pattern, the directional pattern is simplified when the accuracy of the system is satisfied. This simplification improves the speed of calculation and improves the system's operating efficiency. For example, for microwave fixed communication service, in the frequency range of 1 GHz to 70 GHz, the antenna directional pattern model of a fixed wireless system can usually be expressed as Eq. 1.

\[
G(\phi) = \begin{cases} 
G_{m_{\text{ax}}} - 2.5 \times 10^{-3} \left( \frac{D}{\lambda} \right)^2, & 0^\circ \leq \phi < \phi_m \\
G_1 \leq \phi \leq \text{max}(\phi_m, \phi_r) \\
29 - 25 \log \phi, & \text{max}(\phi_m, \phi_r) \leq \phi < 48^\circ \\
-13, & 48^\circ \leq \phi \leq 180^\circ 
\end{cases}
\] (1)

\[
G(\phi) = \begin{cases} 
G_{m_{\text{ax}}} - 2.5 \times 10^{-3} \left( \frac{D}{\lambda} \right)^2, & 0^\circ \leq \phi < \phi_m \\
39 - 5 \log \phi, & \phi_m \leq \phi < 48^\circ \\
-3 - 5 \log \phi, & 48^\circ \leq \phi \leq 180^\circ 
\end{cases}
\] (2)

When $D/\lambda > 100$, the antenna pattern of fixed wireless systems can be expressed as Eq. 2. Where, D——Antenna diameter; $\lambda$——wavelength; $\phi$——Deviation from the antenna’s main axis, degrees; $\theta$——Antenna beam width, degree; $G_{m_{\text{ax}}}$——Gain in the direction of the antenna’s spindle, dBi; $G_1 = 2 + 15 \log \frac{D}{\lambda}$; First side lobe gain; $\phi_m = \frac{\pi}{2} \sqrt{G_{m_{\text{ax}}} - G_1}$, degree; $\phi_r = 15.85(D/\lambda)^{-0.6}$, degree.

If we build the antenna pattern model according to the above ideas, it will encounter many difficulties. Of course, the operation speed will be relatively slow, and it may be too slow to be tolerated when a large number of spatial data calculations are required. Thus, we conducted extensive
research to match different antenna patterns for different communication services. These models can automatically adjust the shape of the lobes based on the actual antenna gain and the half-power angle width. For example, we simplified the directional pattern of a C-band radar as Eq. 3:

$$G(\theta, \phi) = G \exp \left( -\frac{b \phi^2}{(\Delta \phi)^2} \right)$$  \hspace{1cm} (3)$$

where the antenna gain parameter $G$, the half-power angle width parameter $\Delta \phi$ and the form factor $b$ can be adjusted on the input interface. The model of antenna directionality maps for fixed radio communications was modified as Eq. 4-6:

$$G(\phi) = \begin{cases} G - 0.000425 \times 10^{0.1G \phi^2}, & 0^\circ \leq \phi < \vartheta_m \\ 40.925 - 0.25G - 25 \log \vartheta, & \vartheta_m \leq \phi < 48^\circ \\ -1.075 - 0.25G, & 48^\circ \leq \phi \leq 180^\circ \end{cases}$$ \hspace{1cm} (4)$$

$$\vartheta_m = 48.532 \sqrt{G - G_0} \times 10^{-0.05G}$$ \hspace{1cm} (5)$$

$$G = 0.75G - 3.775$$ \hspace{1cm} (6)$$

These modifications and simplifications must comply with actual situation of relevant communication service antenna, and also take into account the requirements for quick calculation and high computational speed. To configure a compliant antenna pattern model for all involved radio communication services, the difficulty of its implementation is quite huge.

In the realization of the algorithm of radio wave propagation, given the characteristic that different frequency carries out propagation calculation in different applications, this paper optimizes the level of algorithm design. On the premise of satisfying the accuracy of the system calculation, this paper selects as simple and efficient algorithm as possible. For example, for the ultra-short-wave band, this paper chooses more accurate propagation for small area-wide propagation calculations. A quick table look-up algorithm was used to implement the situation calculation for a large area, and the system determines the most suitable algorithm. This way greatly improves the calculation speed of the electromagnetic situation.

(3) Calculation according to the coordinates of the principal axis of the antenna and implementation of the conversion of 3 coordinates. The common field strength is to calculate field strength or reception level at certain points on the ground or space satellite orbit. We have solved the problem of spatial field strength mutual conversion among 3D geocenter coordinates (Fig. 4), 3D ground coordinates (Fig. 3), and 3D antenna principal axis coordinates (Fig. 5). The system can give a 3D spatial distribution of the field strength in any coordinate system.

![Fig.3 3D ground coordinates](image3.png)  \hspace{1cm} ![Fig.4 3D geocentric coordinates](image4.png)  \hspace{1cm} ![Fig.5 3D antenna polar coordinates](image5.png)

In the aspect of system development, this method improves the speed of calculation and simplifies programming. In the aspect of practical application, this method is relatively simple and universally achieves compatibility with different calculation requirements, making it possible for the system to analyse and calculate for a variety of battlefield frequency equipment. The propose method breaks through the limitations of current similar software focusing on the communications, and more adapt to the requirements of operational command applications. Both aeronautical navigation and aeronautical mobile communications require knowledge of the distribution of field strengths in specific spatial regions in order to understand, design and control the effective area of control of the aircraft. As long as the real parameters of the ground-based navigation station and the ground-based aeronautical communication station are given, using the method established by this system, it is easy to plan and design the effective control area of the aircraft. For example, ground equipment and the trajectories of air targets can be represented by geocentric coordinates as Eq. 7:
\[\lambda_{a1}, \varphi_{a1}, h_{a1}; \lambda_{b1}, \varphi_{b1}, h_{b1}; \lambda_{a2}, \varphi_{a2}, h_{a2}; \lambda_{b2}, \varphi_{b2}, h_{b2}; \ldots; \lambda_{a_n}, \varphi_{a_n}, h_{a_n}; \lambda_{b_n}, \varphi_{b_n}, h_{b_n};\]

Or as Eq. 8-9,
\[i = 1, 2, \ldots, n; \lambda_{ai} = \lambda_a + i \times \Delta \lambda_a; \varphi_{ai} = \varphi_a - i \times \Delta \varphi_a; h_{ai} = h_a + i \times \Delta h_a; \]
\[\lambda_{bi} = \lambda_a + i \times \Delta \lambda_b; \varphi_{bi} = \varphi_a - i \times \Delta \varphi_b; h_{bi} = h_a - i \times \Delta h_b;\]

where \(\lambda_a = 118.330^\circ, \varphi_a = 28.220^\circ, h_a = 9000, \Delta \lambda_a = 0.025, \Delta \varphi_a = 0.01, \Delta h_a = 0, \Delta \lambda_b = 0.050, \Delta \varphi_b = 0.020, \Delta h_b = 180, n = h_a/\Delta h_a.\) The coordinate parameters of the lower footprint zone \(a\) are associated with the ground equipment, and the coordinate parameters of the lower footprint zone \(b\) are associated with the air targets. However, the field strength at the observation point should be a function of the polar angle, azimuth and distance of the polar coordinates of the antenna, as \(E = E(\theta_i, \phi_i, D_i)\), where the azimuth of the spatial grid \(\phi_{ijk} \leq \lambda_{ijk}\), where
\[\phi_{ijk} = \arccos \left( \frac{\sin \phi_{ijk} - \cos \phi_{ijk} \sin \phi}{\sin \phi_{ijk} \cos \phi} \right), a_{ijk} = \arccos \left( \sin \phi \sin \phi_{ijk} + \cos \phi \cos \phi_{ijk} \cos(\lambda - \lambda_{ijk}) \right).\]

The distance of the spatial grid can be expressed as Eq.10.
\[D_{ijk} = \sqrt{(R + h)^2 + (R + h_{ijk})^2 - 2(R + h)(R + h_{ijk})\cos a_{ijk}}\]

It can be seen that this calculation method meets the requirements for electromagnetic situation analysis of a variety of different radio services, and can also be used for analysis of airborne mobile frequency equipment.

3.2.2. Full band radio wave propagation prediction method

In the field of radio wave propagation analysis and calculation algorithms, this paper has integrated a large number of theoretical models and statistical models of ITU. This paper has considered the geographical environment, the actual deployment of station sites, and the performance of equipment, and realized the scientific calculation of space wave propagation. The algorithm research is mainly based on the actual needs of battles to select the appropriate radio wave propagation model, and according to the actual needs of the system to modify and improve the propagation model. The radio wave propagation model is a description of the propagation characteristics of radio waves in specific environments and frequency bands. The radio wave propagation model is divided into two types, one is a theoretical model, derived from theoretical analysis, and can be expressed as a formula; the other is a statistical model, which is statistically obtained from a large number of actual test data, and is generally expressed as an approximate formula, a chart, etc. Since the propagation phenomenon in the near-Earth range is very complex, there are a large number of propagation models that involve different propagation modes, different propagation environments, and different frequency bands. Electromagnetic situation analysis shows that the system, as a system oriented to operational command applications, must find the location in terms of technology and practicality. It is necessary to ensure the accuracy of calculations and remove unnecessary details. It is necessary to demonstrate the role of operational decision-making aids. Moreover, according to the characteristics of local areas, this paper localized the radio wave propagation model. For this reason, this paper conducts tests and tests, obtained a large number of conclusions, and applied some research results of relevant units, and finally determined eighteen kinds of radio wave propagation models, and its applicable parameters. In the end, this paper applies radio wave propagation prediction methods proposed by ITU-R, URSI, ITS and other agencies, general experience and semi-empirical methods, combines radio wave propagation prediction methods that have been successfully tested and widely used by domestic measurement data, and use basic data of local areas. After a high degree of integration, various types of radio wave propagation prediction models applicable to this project were obtained.

4. System application

4.1. System Application Process

The main process of the simulation system software is divided into the following steps (Fig.6 upper left):
(1) Adding frequency equipment models and user data through the resource management subsystem; (2) By scenario sub-systems, drawing up the intended deployment of the scenario, selecting the frequency equipment model and setting the deployment location and equipment operating parameters; selecting the deployment of the equipment platform and implementing the planning of the trajectory through 2D map icons. And set the running time and loading equipment operating parameters; (3) Through electromagnetic situation calculation and electromagnetic environment analysis subsystem, analyze the electromagnetic characteristics of equipment, and adjust the parameter information of frequency equipment; (4) Analyse the red-and-blue confrontation process through the counter simulation subsystem, and push the result to the visual display subsystem; (5) Through the task scheduling and monitoring subsystem, access to the desired tasks generated by ordinary users, and can specify the red and blue attributes of technical operators, to merge any two operator’s scenarios, and conduct a confrontational analysis on the post-merged scenario; (6) Finally, the task can be analysed and evaluated.

![Fig.6 System application process.](image)

4.2. Application mode
Both confrontation parties firstly conduct electromagnetic situation analysis based on their respective operations, and analyse frequency and power deployed by the battlefield, the scope of the interference equipment, and radar power areas (Figure 6 bottom right), and perform calculation of electromagnetic parameters for the combat process of mobile combat platforms. Secondly, the “back-to-back” countermeasure simulations are performed for equipment operational programs of both confrontation parties (Figure 6, bottom left). According to a comprehensive calculation of the complex electromagnetic environment, both confrontation parties battlefield frequency plan is comprehensive evaluated (Figure 6, upper right). If the expected goal is not achieved, both confrontation parties can revise the frequency plan of their respective programs and re-simulate until the expected goal is achieved, and forming an optimal battlefield frequency countermeasure scheme.

5. Conclusion
This study uses a complex electromagnetic environment confrontation and derivation platform, focusing on the complex electromagnetic environment, frequency equipment, electromagnetic situation, the organization and implementation of the mission planning, equipment application and effect assessment in the battlefield environment, comprehensively improves organization and command capabilities, equipment utilization capabilities, situational analysis capabilities, and planning and confrontational capabilities under the complex electromagnetic environment. This system is aimed at the lack of quantitative calculation and information support methods in the existing experimental training, highlights the use of simulation calculations, and constructs a set of electromagnetic environment information equipment test simulation system based on equipment model calculations, forming computable, deducible, interactive, and connectable experimental simulation capabilities.

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