Research on Fidelity Simulation of Space Electromagnetic Environment Radiation Source

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Abstract. This paper proposes to model and simulate radiation sources in complex electromagnetic environments in space from three aspects of real-time, dynamic and parameter completeness, which solves the problem of fidelity simulation under the high dynamic conditions of multiple radiation sources in the space electromagnetic environment. This paper proposes the parameters covered by the real-time, dynamic and parameter completeness of the radiation source, and designs the basic model, which provides design ideas for the spacecraft's adaptive simulation in the space electromagnetic environment, and provides for the design and development of the spacecraft's anti-jamming capability Technical Reference.

1. Introduction

There are many kinds of radiation sources in the space electromagnetic environment, the forms of radiation signals are diverse, the spatial distribution is complex, and the position of the radiation source changes dynamically. The radiation sources in these space electromagnetic environments include natural environmental radiation sources such as cosmic rays, ionosphere, electromagnetic pulse, static electricity, and unintentional radiation signals and intentional radiation signal sources such as radar, communications, and navigation. In order to improve the anti-interference ability of the spacecraft in the space electromagnetic environment, it is necessary to simulate the space electromagnetic environment through simulation means before launching, and to simulate and calculate the adaptability of the spacecraft in the space electromagnetic environment. It can provide technical reference for the anti-jamming design and development of spacecraft. In the simulation of the space electromagnetic environment, it is faced with the difficult problem of how to realistically simulate radiation sources in different spatial, time, frequency and energy domains.

2. Simulation elements for the fidelity of radiation sources

The main difficulty of radiation source simulation in space electromagnetic environment is reflected in the fidelity of the model. In most documents, the radiation information of the radiation source is generally described by pulse description words (PDW), which specifically includes: pulse carrier frequency, pulse width, In-pulse modulation (phase encoding or frequency modulation), time of arrival (TOA), direction of arrival (DOA) and pulse amplitude. The advantage of this description is that the information characteristics of the radiation source can be clearly expressed, and the modeling and analysis can be accurately performed. The disadvantage is that the number of radiation sources and the
dynamic position change of the radiation source are not considered, and the parameter description of the radiation source is not refined enough.

In the case that the radiation source is limited in the traditional functional simulation, in order to overcome the shortcomings of using the pulse description word to describe the radiation source, and at the same time to achieve the fidelity simulation of the radiation source, the simulation of the radiation source in this paper mainly considers three aspects, including Real-time, dynamic and parameter completeness.

The real-time performance of the radiation source is the primary consideration in simulation. Due to the complex electromagnetic environment in space and the dense distribution of radiation sources, the pulse density in the electromagnetic environment is often very high. There will be two or more pulses arriving at the receiving device port at the same time. The TOA of these pulses is the same. In multi-signal synthesis, these signals arriving at the same time must be synthesized to simulate the actual situation in space more realistically, and the spacecraft can feel the most realistic electromagnetic environment in space, so there is a higher requirement for the real-time performance of the radiation signal. The real-time performance of the radiation signal of the radiation source is described by the signal emission time ($T_{0i}$), pulse repetition interval ($PRI_i$), signal TOA$_i$ and the number ($N_i$) of pulses arriving at the same time at time $\tau$.

The dynamic of the radiation source reflects the dynamic characteristics of the electromagnetic environment in space. Multiple radiation sources are on different moving platforms and their respective moving states, radiating targets from different directions. Therefore, in the synthesis of multiple signals in the space electromagnetic environment, it is necessary to consider whether the DOA of the radiation source signal is within the receiving range of the receiving device. The mobility of the radiation source is described by the radiation source position ($X_i, Y_i, Z_i$), DOA of pulse signal, antenna main lobe beam width and antenna pointing ($\alpha_i$).

The completeness of the radiation source parameters reflects the characteristics of the radiation source itself. In the process of modeling the radiation source, the accuracy of the simulation of the radiation source's own characteristics directly affects the authenticity of the electromagnetic environment simulation.

3. Simulation of the fidelity of the radiation source

3.1. Real-time simulation

The real-time nature of the radiation source is reflected in the accuracy of the pulse arrival time, and the TOA is one of the most important parameters of the pulse flow. TOA is related to the distance between the radiation source and the receiver and the pulse repetition interval ($PRI$) of the radiation source. Different types of radiation sources have different PRIs. The arrival time of the pulse front is mainly related to the pulse emission time and its propagation delay in the atmosphere, while the pulse emission time is related to the PRI.

When we simulate the TOA of pulse, the pulse emission time $t(n)$ is obtained from the PRI, and then the TOA of pulse is obtained according to $t(n)$ and the time delay $\Delta t$. The calculation formula is as follows:

$$TOA = t(n) + R/C$$

(1)

Where $\Delta t = R/C$ is the time required for the radiation source to reach the passive radar receiving end after the pulse is emitted, where $R$ is the linear distance from the passive receiving platform to the radiation source platform, and $C$ is the propagation speed of electromagnetic waves in the atmosphere.

Assuming that the transmission time of the last pulse is $t(n-1)$, the main factor affecting the current pulse transmission time $t(n)$ is the current PRI of the radar. The PRI features of modern new radar systems are very complex, such as fixed, staggered, jittered, staggered jitter, group staggered, group staggered jitter. There are mature models available for PRI of each system from related literature. After getting the PRI, the current pulse emission time $t(n)$ can be obtained.

$$t(n) = t(n - 1) + PRI$$

(2)
During signal synthesis, it is necessary to clarify the number of pulses emitted by the radiation source arriving at the same time. If the number of radiation source pulses is limited, the number of pulses with the same TOA shall be counted according to the above calculation method. When the number of pulses generated by $N$ radiation sources is large, since the arrival time of each signal sequence is independent of each other, within a certain period of time, the statistical stability and no aftereffect are approximately satisfied. According to the stochastic process theory, the number of pulses arriving at the same time within time $t$ satisfies the Poisson distribution. That is, the probability of reaching $N$ pulses in time $t$ as follows:

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad t \geq 0; n = 0, 1, \ldots$$  \hspace{1cm} (3)$$

The average value of arriving pulses in time $t$ is:

$$\sum_{n=0}^{\infty} P_n(t)n = \lambda t$$

$\lambda$ is the average value of arriving pulses in unit time ($t=1$s), From this, the number of pulses $N_i$ arriving at the time $\tau$ can be calculated.

### 3.2. Dynamic simulation

The dynamic characteristics of the radiation source mainly refer to the relative movement characteristics of the radiation source and the receiving device, which is mainly reflected in the DOA of the radiation signal reaching the receiving device. By calculating the DOA, it is possible to filter out which radiation sources have an impact on a certain receiving device. The calculation idea is as follows:

- First, clarify the direction and directional diagram of the transmitting antenna according to the coordinates of the location of the radiation source and the receiving device.
- Calculate whether the receiving device is within the main beam range of the transmitting antenna when the radiation source is at a certain height. If it is within the main beam range of the transmitting antenna, calculate the DOA of pulse, and then judge whether the DOA is within the main beam range of the receiving antenna.
- If the position coordinates of the receiving point are not within the plane range, there is no need to calculate DOA.

DOA is information closely related to the location of the radiation source, and depends on the relative angle between the radiation source and the receiver. When there is relative motion between the radiation source and the receiver, the DOA changes slowly.

DOA is actually the direction in which the electromagnetic wave emitted by the radar reaches the receiving device. Since the electromagnetic wave propagates in a straight line, DOA is the direction of the radiation source platform relative to the receiving platform at the moment of pulse emission. This direction mainly depends on the relative spatial positions of the two platforms. Therefore, we only require the instantaneous spatial relative positions of the two platforms to determine the DOA. Suppose the transmission time of the $n$th pulse is $t$, then the DOA of the pulse to the receiving platform is as follows:

$$\text{DOA}(n) = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \arctan \frac{z'}{x'} \\ \arccos \frac{x'}{R} \end{bmatrix}$$  \hspace{1cm} (4)$$

Among them, $X_V, Y_V, Z_V$ represent the coordinate values of the radiation source in the rectangular coordinate system of the receiving platform, $R$ is the distance from the radiation source to the receiving platform, $\alpha$ is the azimuth arrival angle, and $\beta$ is the pitch arrival angle.

If the radiation source is on the ground and the receiving device is a space target, the coordinate values $X_V, Y_V, Z_V$ of the radiation source in the rectangular coordinate system of the receiving platform need to be calculated according to coordinate conversion.

### 3.3. Parameter completeness simulation

Only when the radiation source's characteristic parameters are complete can it be possible to more accurately simulate its own characteristics. These parameters include not only the real-time parameters
and motion parameters of the radiation source, but also the parameters that reflect its own electromagnetic characteristics.

The complete characteristic parameters of the radiation signal of the radiation source include: working frequency, transmission power, transmission loss, receiver bandwidth, antenna main lobe gain, carrier frequency type, modulation style. Carrier frequency types include single radio frequency, frequency diversity, frequency coding, frequency agility, linear frequency modulation and phase encoding, modulation styles include binary amplitude shift keying (ASK), multi-level amplitude modulation (MAM), digital signal quadrature amplitude modulation (QAM), binary frequency shift keying (2FSK), multi-frequency Shift keying (MFSK), minimum frequency shift keying (MSK), binary phase shift keying (2PSK), and multiple binary phase shift keying (MPSK).

If it is an intentional jamming signal, the complete characteristic parameters of the jamming signal include operating frequency, jammer power, jammer antenna main lobe gain, and interference pattern. Jamming patterns include suppressing interference and deception interference.

Radiation source parameters also include real-time parameters such as signal transmission time \(T_{i0}\), pulse repetition interval \(PRI_i\), time of arrival \(TOA_i\) of pulse and the number \(N_i\) of pulses arriving at time \(\tau\), as well as pulse position, main lobe beam width, dynamic parameters such as antenna pointing and direction of arrival \(DOA\) of pulse.

All radiation sources in the space electromagnetic environment can establish mathematical models based on the above parameters. The general expressions of commonly used signal carriers are as follows:

\[
s(t) = A(t) \cos(\omega_c t + \phi(t))
\]  (5)

Among them, \(A(t)\) is the instantaneous amplitude of the carrier, \(\omega_c\) is the angular frequency of the carrier, and \(\phi(t)\) is the instantaneous phase of the signal. The pulse carrier frequency type and the radiation source model involved in the modulation pattern can be obtained by converting the above expressions.

The expression of the interference signal radiation source model is as follows:

\[
J(t) = U_j x_j(t) \cos[2\pi f_j t + \theta(t) + \phi_0]
\]  (6)

In the formula, \(x_j(t)\) is the interference signal, \(U_j\) is the amplitude of the interference signal; \(\omega_j\) is the carrier center frequency of the interference signal; \(\phi_0\) is the initial phase.

In the space electromagnetic environment radiation source simulation, the time of arrival \(TOA\) of pulse is first determined. The number of pulses arriving at the same time is screened. The \(DOA\) of these pulses arriving at the same time is calculated, and the pulse signal that affects the receiving target is screened again. The signal characteristics of the radiation source, the signal is modeled based on the basic model of the radiation source signal of (5) and (6), and finally the electromagnetic environment characteristics of a certain position in space are calculated by signal synthesis and simulation. Figure1 shows the process of radiating source simulation to construct a space electromagnetic environment.

In the space electromagnetic environment radiation source simulation, the time of arrival \(TOA\) of pulse is first determined, and the number of pulses arriving at the same time is filtered out. Then calculate \(DOA\) of these pulses that arrive at the same time, and filter out the pulse signals that affect the receiving target again. According to the characteristics of the radiation source signal, the signal is modeled based on the basic model of the radiation source signal in (5) and (6), and finally the electromagnetic environment characteristics of a certain position in space are calculated by signal synthesis and simulation. The process of radiating source simulation to build a space electromagnetic environment is shown in Figure 1.
Identify the number of radiation sources in the space

Count the number of pulses of each radiation source

Calculate the time of arrival (TOA) for each pulse

Count the number of pulses arriving at the same time (Ni)

Synthetic signal generates space electromagnetic radiation environment

Establish the radiator signal model

Screening of radiation source pulses that have an impact on the receiving point

Calculate the direction of arrival (DOA) of pulses arriving at the same time

Figure 1. The process of building a space electromagnetic environment by radiating source simulation

4. Conclusion

This paper proposes to model and simulate radiation sources in complex electromagnetic environments from three aspects of real-time, mobility and parameter completeness, and analyzes the parameters of the real-time pulse signal of the radiation source and the mobility of the platform where the radiation source is located. Then we carried out the model establishment. The real-time parameters, mobility parameters and electromagnetic characteristic parameters of the radiation source are clarified and refined.

This paper proposes the basic model of the radiation source signal, which solves the problem of fidelity simulation under the high dynamic condition of multiple radiation sources in the space electromagnetic environment. A more realistic space electromagnetic signal environment is constructed, which provides design ideas for the adaptive simulation of spacecraft in the space electromagnetic environment. It can further provide technical reference for the anti-jamming design and development of spacecraft.

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