Research on Multiple Signal Synthesis Methods in Space Electromagnetic Environment Simulation

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Abstract. This paper proposes three spatial electromagnetic signal environment concepts from three levels: general electromagnetic signal environment, relative electromagnetic signal environment and electronic warfare signal environment. It can solve the difficult problem of comprehensive, accurate and targeted description of the electromagnetic environment in the space electromagnetic environment simulation of the spacecraft. This paper studies the synthesis method of various types of signals contained in the three electromagnetic signal environments in a certain area, and provides a reference for the accurate simulation of the dynamic and intuitive, hierarchical electromagnetic environment situation in a certain area of space.

1. Introduction
Space electromagnetic environment simulation is the statistical, calculation, analysis and synthesis of the types, attributes, characteristics and motion distribution of various electromagnetic signals in the space where the spacecraft is located, and use two-dimensional or three-dimensional graphics, images, charts, analysis reports and other forms to fully demonstrate the electromagnetic situation in space. Space electromagnetic environment signals include natural electromagnetic signals in space, unintentional electromagnetic signals and intentional electromagnetic signals, these signals have a wide variety, complex spatial distribution, and rapid frequency changes. How to accurately describe these spatial electromagnetic environments and how to synthesize signals from different spatial, time, frequency and energy domains in a certain area, then form a dynamic, intuitive and hierarchical complex electromagnetic environment situation, which is a key issue facing the current space electromagnetic environment simulation.

2. Classification of Space Electromagnetic Signal Environment
The quantitative description of the electromagnetic signal environment in space is closely related to a spacecraft in space as a receptor. From the perspective of a spacecraft in space as the target of the electromagnetic signal environment in space, we classify the electromagnetic signal environment in space into general electromagnetic signal environment, relative electromagnetic signal environment and electronic warfare signal environment according to different levels.

2.1. The general electromagnetic signal environment (Eg)
The general electromagnetic signal environment refers to the objective, comprehensive, and macroscopic electromagnetic environment in a specific area of space that has nothing to do with the
spacecraft as the susceptor. It is represented by $E_G$. It is a general electromagnetic signal environment, not for a specific receiving device. It covers all the radiation sources within the space that can generate field strength in the area, including cosmic rays, ionosphere and other space natural electromagnetic environment signals, man-made unintentional radiation signals and man-made intentional radiation signals. It can visually display the distribution of electromagnetic signals in the space area, the occupancy of electromagnetic spectrum and the distribution of electromagnetic signal strength, etc.

2.2. The relative electromagnetic signal environment($E_R$)
The relative electromagnetic signal environment refers to the electromagnetic environment formed by unintentional signals and intentional signals that can affect a spacecraft susceptor in space. It is represented by $E_R$. It is a relative electromagnetic signal environment. In the same space electromagnetic environment, different frequency equipment has different susceptibility to electromagnetic signals, and the resulting electromagnetic signal environment is also different. The radiation sources covered by the relative electromagnetic signal environment are a subset of the radiation sources in the general electromagnetic signal environment, it screens out radiation that have an impact on a specific spacecraft from general electromagnetic environment radiation sources, including unintentional electromagnetic signals and intentional electromagnetic signals. The relative electromagnetic environment can accurately show the distribution of radiation sources that affect a specific spacecraft, the time and space occupation of the electromagnetic spectrum, and the distribution of signal strength, etc.

2.3. The electronic warfare signal environment($E_w$)
The electronic warfare signal environment refers to the interference signal environment that intentionally radiates to a specific spacecraft within a specific period of time. It is represented by $E_w$. It is a targeted electromagnetic signal environment that only includes intentional radiation signals, and the radiation sources it covers are a subset of the radiation sources in the relative electromagnetic signal environment. The counter electromagnetic signal environment can show the layout of intentional radiation sources, spectrum usage, interference intensity distribution for a specific spacecraft.

3. Multiple Types of Signal Synthesis Method

3.1. Signal synthesis in general electromagnetic signal environment
The general electromagnetic signal environment $E_G$ in the space area is composed of signals radiated by $N$ radiation sources and scattering sources at the same time. Due to the difference in the time when the signals of various radiation sources reach a certain point, the radio frequency pulses $S(i,t)$ that reach a certain point at the time $t$ can be sequentially expanded into a pulse sequence:

$$S(i,t) = \{S(i,j)\}_{j=1}^{M_i}$$

In formula 1, $S(i,j)$ is the $j$th pulse of $S(i,t)$, and $j$ is the number of pulses arriving at a certain radiation source at time $t$, $j=1, 2, \ldots, M_i$; $i$ represents the serial number of the radiation source, $i=1, 2, \ldots, N$.

If the number of pulses generated by $N$ radiation sources is limited, the pulse arrival time (TOA) of each pulse can be calculated first, and then the number of pulses with the same TOA can be counted as $Nt = \sum_{i=1}^{N} ij$. Therefore, the signal received at a certain point in the general electromagnetic signal environment is the superposition of $Nt$ signals radiated by $N$ radiation sources. Using the electromagnetic wave propagation equation and the spatial geometric relationship, the synthesized signal at the observation point $P_{\mu}(i)=[x_{\mu}, y_{\mu}, z_{\mu}]^T$ in space can be obtained as follows:
In formula (2),

- \( N_c \) — The number of radiation sources;
- \( M_i \) — The number of pulses that arrive at the i-th radiation source at time \( t \);
- \( P_{ij} \) — The transmit power of the jth pulse of the i-th radiation source;
- \( G_{ij} \) — Antenna gain affected by antenna pattern and signal arrival angle;
- \( R_{ij} \) — The distance to the observation point;
- \( L_{ij} \) — Attenuation caused by environmental factors;
- \( s(i,t) \) — The signal form of the i-th radiation source;
- \( c \) is the speed of light, \( c = 3 \times 10^8 \) m/s;
- \( R_{ij}/c \) represents the transmission delay between the observation point and each radiation source.

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, the statistical stability and no aftereffect are approximately satisfied within a certain period of time, according to the random process theory, the number of pulses arriving at the same time within time \( t \) satisfies the Poisson distribution. Therefore, the probability of reaching \( n \) pulses in time \( t \) is as follows:

\[
P(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \quad t \geq 0; n = 0,1,\ldots
\]  

(3)

The average value of the arriving pulse in time \( t \) is \( \sum_{n=0}^{\infty} P_n(t) n = \lambda t \). \( \lambda \) is the average value of the arriving pulse in unit time (t=1s), also known as the signal flow density of \( E_G \) after synthesis.

Then the synthesized signal at the space observation point \( P_x = [x, y, z] \) is as follows:

\[
S(P_x, \ t) = \sum_{i=1}^{N_c} \sum_{j=1}^{M_i} \left( \frac{P_{ij} G_{ij}}{4 \pi R_{ij}^2 L_{ij}} \right)^{1/2} s\left( i, t - \frac{R_{ij}}{c} \right)
\]  

(4)

In formula (4), \( f_{cl} \) is the average pulse repetition frequency of the i-th radiation source, and \( p_i \times f_{cl} \) is the number of pulses of the i-th radiation source in 1 second, \( p_i = P_n(t) \); Other parameters are consistent with the meaning in formula (2).

The Fourier transform is performed on \( S(P_x, \ t) \) to obtain the frequency domain data of the received signal at the space test point \( P_x \), and then the electromagnetic radiation intensity generated by the general electromagnetic signal environment in the space can be analyzed.

### 3.2. Signal synthesis in relative electromagnetic signal environment

According to the definition of the relative electromagnetic environment \( E_R \), the relative electromagnetic environment is for a specific frequency in space. The electromagnetic environment it feels is not only related to the objective electromagnetic environment, but also related to its own characteristics. The specific frequency equipment is based on the general electromagnetic signal environment \( E_G \) formed in space. According to the equipment’s own use, electromagnetic characteristics and working mode, it obtains relevant information from \( E_G \) and makes appropriate to \( E_G \). The electromagnetic environment formed by the radiation source that can make the specific frequency equipment react is the relative electromagnetic environment, and the factor involved in the reaction is a finite subspace \( D \), \( D = \{\Omega_{RF} \otimes \Omega_{AOA} \otimes \Omega_{PW} \otimes \Omega_p \}, \Omega_{RF}, \Omega_{AOA}, \Omega_{PW}, \Omega_p \) is specific frequency equipment to signal carrier frequency, reaching direction, pulse width, and signal power, \( \otimes \) is direct. The relative electromagnetic signal environment \( E_R \) formed for a particular frequency equipment is a subset of the general electromagnetic signal environment \( E_G \):

\[
E_R = \bigcup_{i=0}^{M_i-1} \{s_i(j)|s_i(j) \in D\}_{j=1}^{M_i}
\]  

(5)
N is the number of radiation sources, \(i=0, 1, \ldots, N-1\); \(j\) is the number of pulses, \(j=1, 2, \ldots\), \(M_i\), then the total number of pulses is \(N_t=N \times M_i\). The greater the detection range involved in the factors in the limited subspace \(D\), the more radiation signal entering the \(E_R\). However, relative to \(E_G\), the number of radiation sources \(N_t\) in the \(E_R\) is limited, and the formula of the synthesis signal at a particular frequency equipment \(P_R\) is as follows:

\[
S(P_R, t) = \sum_{i=1}^{N_t} \sum_{j=1}^{M_i} \left( \frac{P_i G_i}{4\pi R_i^2 L_i} \right)^{1/2} s\left( i, t - \frac{R_i}{c} \right)
\]

(6)

\(N\) is the number of radiation sources that affect specific frequency equipment, and other parameters are the same as the meaning of formula 2.

The Fourier transform is performed on \(S(P_R, t)\), which can obtain frequency domain data of the received signal at a particular frequency equipment \(P_R\), so that the electromagnetic radiation intensity generated by the relative electromagnetic signal environment of the space can be analyzed.

3.3. Signal synthesis in electronic warfare signal environment

The source of radiation in the electronic warfare signal environment \(E_w\) is a human intentional interference source, which has strong targeted. The electronic warfare signal environment is for a particular frequency equipment in the space, the electromagnetic environment it feels is a intentional signal environment generated by the set of radiation sources in relative electromagnetic signal environment \(E_R\), and its radiation source is a subset of relative electromagnetic signals, that is \(E_w \subseteq E_R\), the formula as follows:

\[
E_w = \bigcup_{i=1}^{k} \{ s_i(j) | s_i(j) \in D \}^{M_o}_{j=1}
\]

(7)

\(k\) is the number of intentional radiation sources, \(k \leq N\); \(M_o\) is the number of pulses, the total number of pulses is \(N_o = k \times M_o\). In general, the number of intentional radiation sources in the electronic warfare signal environment is limited, and these radiation sources are specially designed for specific devices in terms of signal frequency, reaching direction, pulse width, and signal power. The synthesis signal at the specific device \(P_w\) is as follows:

\[
S(P_w, t) = \sum_{i=1}^{k} \sum_{j=1}^{M_o} \left( \frac{P_i G_i}{4\pi R_i^2 L_i} \right)^{1/2} s\left( i, t - \frac{R_i}{c} \right)
\]

(8)

\(k\) is the number of intentional radiation sources, \(M_o\) is the number of pulses, and other parameters are the same as the meaning of formula 2.

The Fourier transform is performed on \(S(P_w, t)\), which can obtain frequency domain data of the received signal at a particular frequency equipment \(P_w\), so that the electromagnetic radiation intensity generated by the counter electromagnetic signal environment of the space can be analyzed.

4. Conclusion

It is seen from this paper that no matter how complicated in space electromagnetic signal environments, the spatial electromagnetic environments can be classified by the general electromagnetic signal environment, relative electromagnetic signal environments, and electronic warfare signal environments. It can perform hierarchical display of the space electromagnetic signal environment situation where the spacecraft is located, and can basically solve the problem of difficult accurate, comprehensive and targeted description of the space complex electromagnetic environment situation. Then we synthesize the various types of signals contained in the three electromagnetic signal environments to form a dynamic and intuitive, hierarchical synthetic electromagnetic environment, which can provide a reference for accurate simulation of the electromagnetic environment in the space area where the spacecraft is located.
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