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A Brief Discussion on a Novel Method for Practical Date Measurement of Radiation Efficiency in Low-Frequency Communication Synchronization Antennas

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Abstract

With the continuous popularity of domestic radio watches and clocks, the importance of low-frequency radio stations has become increasingly significant. However, as domestic low-frequency radio stations have been established for over 20 years, with the erosion of time, radio antennas and ground networks have suffered varying degrees of damage, leading to a potential decline in the broadcasting efficiency of the radio stations. Especially in recent years, with the continuous development of technology, industries related to time accuracy have increasingly higher demands, surpassing the precision provided by traditional quartz clocks, which are no longer sufficient to meet market needs. To verify the actual transmission efficiency of existing low-frequency radio stations and to meet the demands of a wide range of radio users, this paper adopts a new testing method specifically designed for low-frequency communication signals for testing and analysis. Relevant parameters are organized, and communication data on the antenna parameters during the initial station construction period are collected and organized. The two sets of data are then analyzed and compared to validate the antenna efficiency of low-frequency stations' output signals. Based on the relevant verification data, the extent of damage to the low-frequency antenna ground network is determined, providing reference information for the subsequent repair of antennas and ground networks.

Keywords: communication, date, low-frequency radio stations, ground network, antenna efficiency

1. Introduction

Due to our late start, the relevant testing data is incomplete. Especially for longwave radio stations, the testing methods are not perfect, and there are also many types of longwave communication radio stations. How to explore a complete method for testing longwave communication will fill the current gap.Due to the low working frequency of long-wave transmitters, their wavelengths are much larger than the geometric dimensions of broadcasting antennas, significantly impacting radiation energy. In order to improve radiation efficiency, large copper wire ground networks are generally laid underground at a depth of 30-50 centimeters at the base of long-wave antennas. The ground network buried underground is susceptible to soil corrosion or human cultivation damage. The more breakpoints there are in the copper wires below the ground surface, the lower the radiation efficiency of the antenna system. Therefore, understanding the intact status of the ground network is essential to ensure the radiation efficiency of the antenna [1].This article analyzes and compares relevant test data, and expresses the relevant parameters using actual data to demonstrate the antenna radiation efficiency of low-frequency timing.

2. Importance of Low-Frequency Antennas and Their Efficiency

2.1 Low-frequency antenna systems

Low-frequency antennas utilize a single umbrella antenna with excellent geometric symmetry, allowing the ground network to achieve maximum efficiency and enhance the system's transmission efficiency. The radiation's horizontal component is minimized in single umbrella antennas, reducing energy losses in the antenna system [2]. The theoretical calculations for the initial construction of low-frequency antenna systems are performed on a 1/12 scale model for comparison with experimental values. The low-frequency transmission antenna has a height of 250 meters, employing 45° three-sided four-layer guy wires to increase the effective height, enhance antenna capacitance, and incorporate 12 umbrella wires, each 180 meters from the top, as part of the antenna radiating body [3].

2.2 Importance of low-frequency antenna efficiency for radio product users

Low-frequency time code synchronization is currently an advanced international radio time synchronization technology and is favored by the International Telecommunication Union (ITU) as a new generation time synchronization technology. Low-frequency time synchronization refers to the lower working frequency of the timing radio waves, and the diverse output methods of the waves (providing analog, digital standard seconds, or other signals for different users). Globally, low-frequency time synchronization technology has been widely used in several countries, with Germany being the first to successfully develop and widely apply this technology globally. Subsequently, the United States, Japan, and the United Kingdom have also successively developed and applied low-frequency time code technology [4]. Based on the varying needs of users, low-frequency time synchronization primarily serves military and civilian users. With the increasing number of civilian time synchronization users, the emphasis on civilian applications has gradually increased, such as for mobile networks, power collection systems, transportation measurement systems, financial systems, scientific research, and other relevant areas [5]. Since the completion of low-frequency radio stations in China in 2008, the number of low-frequency radio product users has continuously increased. Particularly, with many provinces adopting radio-controlled clocks for exams in recent years, low-frequency time code has become increasingly important. The efficiency of antennas significantly influences the use of radio products by users. According to the formula for calculating field strength and antenna radiation efficiency (as shown in Equation 1):

$$E = E_0 + 10 \log P_X \tag{1}$$

(E_0 is the received field strength, and PX is the radiation efficiency of the transmitting antenna)

From the above calculation formula, it is evident that the radiation efficiency of the broadcasting antenna directly affects the field strength at the receiving point. To ensure that radio products always operate in a favorable reception environment, it is crucial to maintain a sufficiently high radiation efficiency of the antenna.

2.3 Role of antenna efficiency in green energy

Low-frequency radio stations operate as high-power stations, and continuous broadcasting is preferable to ensure optimal user experience. From a green energy perspective, increasing the antenna's radiation efficiency under the condition of maintaining the same receiving field strength can reduce the transmitter's power. This not only ensures a constant numerical value of antenna radiation field strength but also indirectly reduces significant costs while achieving the goal of low carbon emissions. For instance, an antenna with 85% efficiency (-0.71 dB) compared to one with 70% efficiency (-1.55 dB) can reduce transmission power by 18% while maintaining the same coverage [6].

3. Test and Analysis Method

Calculating antenna radiation efficiency involves several parameters, including the antenna's input resistance, antenna input current, field strength testing distance, measured field strength, antenna's effective height, and radiation resistance of the antenna. The field strength value and the effective height of the antenna need to be converted into numerical values based on the corresponding test data.

3.1 Test of antenna input impedance

The input impedance of the antenna varies with the frequency of radio waves. In this study, a substitution method was used to test the input impedance of low-frequency antennas. To ensure the accuracy of the numerical values, the test results were compared with relevant values from the initial construction period of the low-frequency station to validate the accuracy of the current measurements.

The antenna input impedance was tested using the substitution method are presented in Table 1, Figure 1, and Figure 2:

Table 1 20240125 Input Impedance of Tested Antenna

Serial No.	Frequency Hz	Tuning inductance uH	Resistance Ω	Reactance Ω	Remark
1	40	1483	3.28	-372.7	Cannulated Inductance
2	50	903.7	1.77	-283.9	
3	60	676.2	12.8	-254.9	
4	62	469.9	4.62	-183.1	
5	68	384.1	4.06	-164.1	
6	70	345.5	3.78	-151.9	
7	80	219.3	5.09	-110.3	
8	90	128.6	5.94	-72.7	
9	100	61.9	6.47	-38.9	

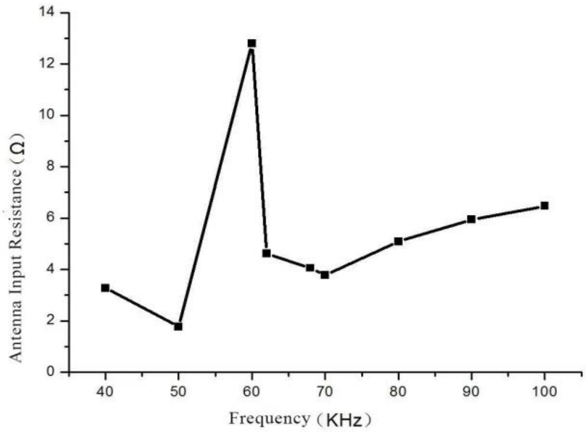

Figure 1 Antenna Input Resistance

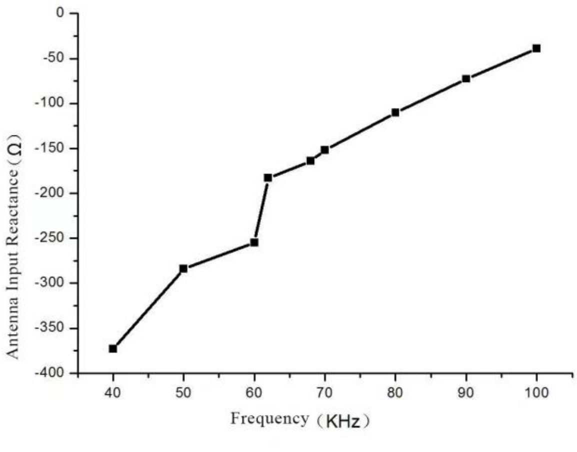

Figure 2 Antenna Input Reactance

From the above test data, it can be observed that the input resistance of the antenna experiences certain fluctuations due to the influence of inductive effects, but overall, the trend is an increase with the rise in frequency. The input reactance of the antenna also increases with the frequency, with a self-resonant frequency of approximately 112.7 kHz.

As the frequency decreases, the magnitude of the antenna's reactance increases, necessitating a gradual increase in the tuned inductance. Simultaneously, since the tuned inductance is a dissipative component, the Q value of small hollow inductors is around 50. Consequently, the introduced losses during low-frequency tuning gradually increase, causing a reduction in current under a certain voltage. The determination of the tuning point during tuning becomes less accurate and sensitive. Therefore, existing low-power devices cannot accurately test states with extremely high reactance magnitudes, requiring testing with high-voltage equipment.

Comparisons between the current measurement results and the data from the tests conducted on December 23, 2023, and the acceptance tests are presented in Table 2, Table 3, Figure 3, and Figure 4:

Table 2 20231223 Input Impedance of Tested Antenna

Serial No.	Frequency Hz	Tuning inductance uH	Resistance Ω	Reactance Ω	Remark
1	30	2544	3.78	-479.4	Cannulated Inductance
2	35	1958	3.22	-430.6	
3	40	1442	3.5	-362.4	
4	50	848	3.4	-266.4	
5	58	589.5	3.32	-214.8	
6	63	445.7	3.54	-176.4	
7	68	380.2	4.26	-162.5	
8	73	294.5	4.33	-135.1	
9	78	238.2	4.6	-116.7	
10	80	213.6	4.69	-107.4	
11	90	115.6	5.75	-65.4	
12	100	57.9	7.2	-36.4	
13	105	35.2	7.62	-22.1	

Table 3 Acceptance input impedance of tested antenna

Serial No.	Frequency Hz	Resistance Ω	Reactance Ω
1	62.5	2.34	-202.9
2	64.5	2.90	-191.7
3	66.5	3.19	-181.2
4	68.5	2.51	-172.7
5	70.5	2.65	-161.6
6	72.5	3.03	-154.0
7	74.5	2.42	-144.5

Through the comparison of data, it is found that with the erosion of time, the resistance and reactance of the low-frequency antenna have increased compared to the initial construction phase. Taking various influencing factors into account, the tentative value for the antenna resistance is set at 4.06 ohms.

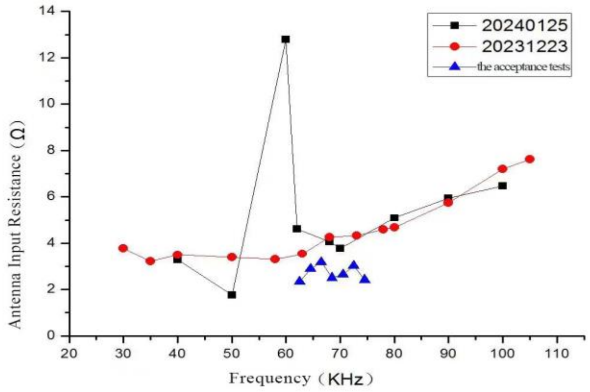

Figure 3 Antenna Input Resistance Comparison

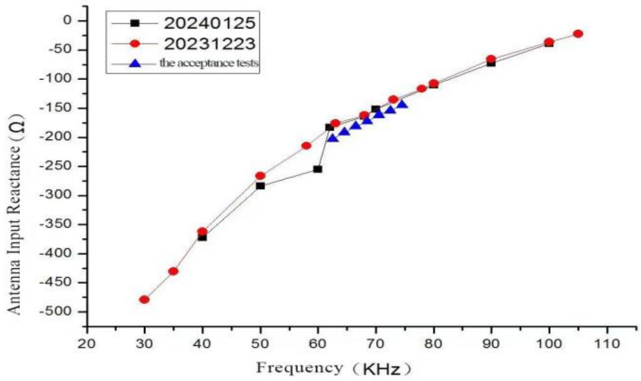

Figure 4 Comparison of antenna input reactance

3.2 Testing based on directional fixed-point radiation field strength

In consideration of the non-directionality of single-tower radio wave propagation [7], and to further verify the damage to the current low-frequency station's ground wave propagation, the following principles were established for the fixed-point radiation field strength testing;

(1) The testing distance should not be too far to avoid excessive ground wave attenuation, and the test points should be evenly distributed around the antenna. Considering points located at 2-3 wavelengths from the antenna, approximately 9-15 km.

(2) When selecting test points, attention should be given to a flat and open environment, away from traffic lanes, power plants, high-voltage lines, and communication optical cables. It is essential to avoid obstruction from tall buildings and plants, aiming for as low background noise as possible.

Due to the relatively short distance, minimal changes in environmental conditions, and low ground wave attenuation at this operating frequency, the differences in ground wave attenuation along different paths can be neglected [8]. After correcting the measured field strength values at each test point to the same output parameters, the results can be used to infer the corresponding outcomes.

The test method is as follows:

Under normal operating conditions (operating frequency 68.5 kHz), maintaining a given broadcast power (60 kW) to keep the antenna's output current stable, the distance between the transmission point and test points is determined using a satellite positioning device. The received field strength at each test point is measured using a calibrated field strength meter, while simultaneously recording the input current at the transmitter end antenna.

(Due to the confidentiality of the data, real test data is temporarily represented by letters.) The measurement diagram is illustrated in Figure 5;

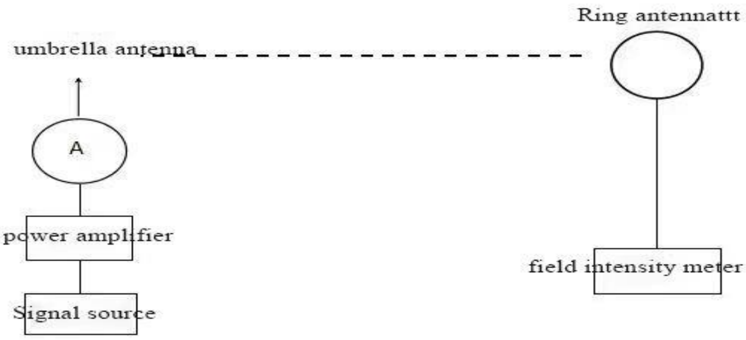

Figure 5 Field strength measurement

The relevant specific field strength measurements are given in Table 4 below:

Table 4 Field strength test data

Distance km	13.30	13.45	12.89	9.88	10.13	10.27	10.50	13.08	12.92	12.52	12.72	13.33
Field strength dbuv/m	a	b	c	d	e	f	g	h	i	j	k	l

We measure the field strength in dbuv/m, and the formula is converted to v/m. The conversion formula from the field strength is as follows:

$$E_0 = 10^{\left[\frac{(E-120)}{20}\right]} \quad (2)$$

Where: E is the field strength at the receiving point (dbuv/m);

The calculated data are as follows Table 5:

Table 5 Converted field strength test data

Distance m	13.30	13.45	12.89	9.88	10.13	10.27	10.50	13.08	12.92	12.52	12.72	13.33
Field strength v/m	a1	b1	c1	d1	e1	f1	g1	h1	i1	j1	k1	l1

Compared to the field strength measurements, the statistics for antenna input current are relatively straightforward. Sampling can be directly performed at the antenna input, with a recorded value of 130A.

4. Analysis and Calculation of Measurement Results

In addition to the field intensity measured at the peripheral fixed point, the input current of the antenna, the resistance, the operating frequency of the transmitter and the power of the transmitter, there are two other important parameters for the calculation of radiation efficiency. That is, the effective height of the antenna and the radiation resistance of the antenna.

4.1 Calculation of effective antenna height

The so-called effective height of the antenna is that if there is a uniform distribution of current on a vertical antenna, the uniform current is equal to the maximum current on the actual antenna, and the radiation field intensity generated is the same as that of the actual antenna, the length of the assumed vertical antenna is the effective height of the actual antenna [9]

Typically, the commonly used method involves first measuring the effective vertical field strength in the radiation zone and the current at the base of the antenna. Subsequently, the effective height of the tested antenna model is calculated using the Sommerfeld-Johnson-VanderPol ground wave field strength formula [10]:

$$h_e = \frac{\mathrm{E}\,\lambda\,\mathrm{D}}{120\pi I} \tag{3}$$

Where, *E* is the field strength (mv/m);

λ is the wavelength (m);

D is the distance (km);

I is the feed current (A) at the bottom of the antenna;

The unit of h_e is m.

Taking the measured field strength, operating wavelength, and input current of the transmitting antenna into Equation (1), the effective height of the antenna can be obtained. The relevant results are presented in Table 6;

Table 6 Effective height calculation results of antenna

Serial No.	Distance (KM)	Field Strength (dbuv/m)	Field Strength (v/m)	Input Current (A)	Effective height (m)
1	13.30	A2	A3	130	A4
2	13.45	B2	B3	130	B4
3	12.89	C2	C3	130	C4
4	9.88	D2	D3	130	D4
5	10.13	E2	E3	130	E4
6	10.27	F2	F3	130	F4
7	10.50	G2	G3	130	G4
8	13.08	H2	H3	130	H4
9	12.92	I2	I3	130	I4
10	12.52	J2	J3	130	J4
11	12.72	K2	K3	130	K4
12	13.33	L2	L3	130	L4

4.2 Calculation of antenna input resistance

The operational system of the long-wave radio station comprises three main components: transmitter, feeder, and antenna. In comparison to the transmitter and feeder, the transmitting antenna can be considered equivalent to antenna impedance [11]. The antenna impedance consists of two parts: the radiation impedance with radiated energy and the resistance and reactance due to antenna losses and mismatch. If the transmitter's output power is Pt, considering modulation at the rear end of the transmitter and the mismatch and losses in the feeder, the actual power fed back to the antenna, Pain, must be less than the transmitter's output power Pt. If only mismatch is considered without taking into account other factors, the antenna input power is equal [12];

$$P\text{ain} = P_{\text{t}} - P_{\text{ref}} = \left(1 - |\Gamma A|2\right) \times P_{\text{t}(5)} \tag{4}$$

Where ΓA is the reflection coefficient of the feed line, and |ΓA| is the modulus of the reflection coefficient, which should be equal to the ratio of the reflected wave voltage Uref to the incident wave voltage Uin. At the antenna port, its value is equal to

$$|\Gamma A| = \frac{(ZA - Z0)}{ZA + Z0} \tag{5}$$

Where Z0 is the characteristic impedance of the transmission line;

From the above equations, it is evident that to increase the antenna's output power, it is essential to reduce impedance during the power transmission process. According to the formula for calculating antenna radiation resistance, it is as follows:

$$R = 160 * \pi 2 * \left(\frac{h_e}{\left(3 * 10^8\right) \div \left(H_1 * 10^3\right)} \right)^2 \tag{6}$$

Where: R is the radiation resistance of the antenna (Ω); PI is the output power of the transmitter (Kw); h_e is the effective height of the antenna (m); H1 operating frequency (Hz);

Substituting the calculated effective height and operating frequency of the antenna into equation (7) yields the corresponding radiation resistance for each direction. The respective calculation results are presented in Table 7;

Table 7 Radiated resistance calculation results of antenna

Serial No.	(KM) Distance (KM)	Field Strength (dbuv/m)	Field Strength (v/m)	Input Current (A)	Input Resistance (Ω)	Effective height (m)	Radiation resistance (Ω)
1	13.30	A2	A3	130	4.06	A4	A5
2	13.45	B2	B3	130	4.06	B4	B5
3	12.89	C2	C3	130	4.06	C4	C5
4	9.88	D2	D3	130	4.06	D4	D5
5	10.13	E2	E3	130	4.06	E4	E5
6	10.27	F2	F3	130	4.06	F4	F5
7	10.50	G2	G3	130	4.06	G4	G5
8	13.08	H2	H3	130	4.06	H4	H5
9	12.92	I2	I3	130	4.06	I4	I5
10	12.52	J2	J3	130	4.06	J4	J5
11	12.72	K2	K3	130	4.06	K4	K5
12	13.33	L2	L3	130	4.06	L4	L5

From the above calculation results, it can be observed that the measured field strengths, effective heights, and radiation resistances for the selected 12 test directions are all different. However, there is a clear correlation: directions with larger effective antenna heights tend to have larger measured field strengths and radiation resistances.

4.3 Antenna radiation efficiency

Antenna efficiency refers to the ratio of the radiation efficiency P_r to the antenna input power P_i [13]. Since low-frequency antennas fall into the category of small antennas [14], their effective height is much smaller than their own wavelength. When combined with a coordinating matching circuit, the radiation power of a small antenna depends on two aspects: its own losses and the losses of the coordinating matching circuit. Its equivalent circuit can be represented by inductance, capacitance, and resistance, as shown in the relevant equivalent circuit diagram in Figure 6:

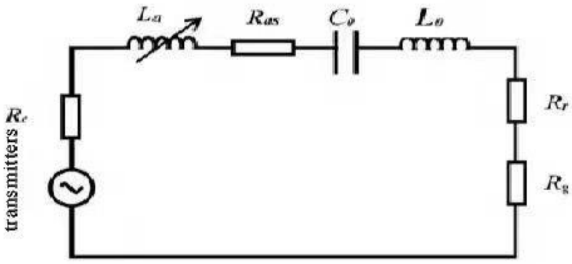

Figure 6 Equivalent circuit of transmitting system

In the above equivalent circuit diagram, R_e represents the internal resistance of the transmitter, and L_a and R_{as} are the loss resistance of the coordinating matching inductor and coil, respectively [15]. C_o corresponds to the static capacitance of the antenna, and the equivalent inductance L_o along with the antenna radiation resistance R_r and ground loss resistance R_g represent the losses of the antenna itself. When the antenna system works in proper coordination with the transmitter, the energy of the broadcast signal is transmitted from the transmitter without feedback. Therefore, the efficiency of the antenna system can be approximately expressed as:

$$h = \frac{Rr}{Ras+Rg+Rr} \tag{7}$$

In the above formula, $R_{as+}R_{g+}R_r$ is the input resistance of the antenna. Substituting the corresponding data from Table 7 into the formula will yield the antenna radiation power for the respective directions, as shown in Table 8 below:

Table 8 Antenna radiation efficiency in the corresponding orientation.

Serial No.	(KM) Distance (KM)	Field Strength (v/m)	Input Resistance (Ω)	Effective height (m)	Radiation resistance (Ω)	Efficiency (%)
1	13.30	A3	4.06	A4	A5	A6
2	13.45	B3	4.06	B4	B5	B6
3	12.89	C3	4.06	C4	C5	C6
4	9.88	D3	4.06	D4	D5	D6
5	10.13	E3	4.06	E4	E5	E6
6	10.27	F3	4.06	F4	F5	F6
7	10.50	G3	4.06	G4	G5	G6
8	13.08	H3	4.06	H4	H5	H6
9	12.92	I3	4.06	I4	I5	I6
10	12.52	J3	4.06	J4	J5	J6
11	12.72	K3	4.06	K4	K5	K6
12	13.33	L3	4.06	L4	L5	L6

5. Conclusion

Through a series of repeated tests, ensuring the precision of data from each selected test point, and then through a sequence of reviews, filtering, and calculations, the radiation efficiency of the low-frequency radio station's antenna is objectively reflected in the form of data. After comparing the final calculated data results with the original site building data, it can be seen that, it is evident that there is a significant difference in the antenna radiation efficiency in various directions. The efficiency, which was initially over 70% at the time of construction, has decreased to a smaller value. This decrease in efficiency will bring some variations to the reception and decoding for radio users. The next step in the process involves analyzing the reasons behind the decline in antenna efficiency, objectively solve relevant problems through the form of data to thoroughly address the corresponding issues. Given the increasing number of related communication stations in the later stage, this method will also provide reference experience for future station testing. This data analysis method for measuring the radiation efficiency of low-frequency timing antennas is a relatively novel approach. It is believed that with the subsequent construction of a large number of communication radio stations, this testing method for communication radio stations will be widely applied. This method will also fill the current gap in testing communication radio stations in China.

Reference

[1] Shen Daicheng, (2020). Medium Wave Broadcasting Antenna Composition Principle and Analysis of the Influence of Ground Network on Transmitter Output Power. Research on Digital Media (12), 54-56.

[2] Liu Jianguo, Gao Wanming, Chen Guanglin, Research on the Physical Characteristics of Antennas for BPL Time Dissemination Systems. Modern Electronics Technique, 2012, 35(9): 57-61.

[3] Cao Cheng. Research on Inverted Cone Long Wave Transmitting Antenna. Modern Navigation, 2019, 10(06): 436-439.

[4] Hang Yinli, Liu Linghui, and Shi Wei. Intelligent Electricity Meters Based on Low Frequency Time Code Active Timing. Science and Technology Vision, 2023, 13 (35): 77-79

[5] Guo Lili, Zhuang Xianwei, Wang Bailing. Design of JJY low-frequency radio wave timing receiver based on MCS-51. Automation Technology and Application, 2010, 29 (08): 61-65[6] Liu Xu. Research on the Related Technologies of Base Station Antenna Efficiency. Mobile Communications, 2022, 46 (03): 21-25.

[7] Gong Zhengxia, Li Youcai, Shi Boyong. Comprehensive Defense Capability Evaluation of Long Wave VLF Fixed Communication Station Based on FCE and AHP. Ship Electronic Engineering, 2016, 36 (12): 127-132.

[8] Zhang Yong, Miao Jinqiang, Wang Yong, Liu Guanshi, Sound Propagation Model and Dissipation Mechanism of Saturated Sandy Sediments Based on Biot Theory. Acta Acustica, 1-16.

[9] Wang Yueqing, Wang Xianyi, Wang Jian et al; Radio Wave Propagation Model Selection and Field Strength Prediction Method. Publishing House of Electronics Industry: 201501.215.

[10] Sun Shengli, Li Yunhong. Research on Electrical Performance of VLF Umbrella Antenna. Ship Electronic Engineering, 2016 (6): 59-60.

[11] Li Chaowei, Lv Shanwei. A Simple and Effective Method for Calculating Antenna Impedance Based on FDTD. Acta Electronica Sinica, 2001, (12): 1635-1637.

[12] Gu Neng. Circuit Parameters of Antenna. Broadcasting Realm (Broadcasting and Television Technology), 2008, (03): 34-36.

[13] Hu Sumou, Li Liang, Ding Zuoya. Radiation Efficiency Analysis of T-type VLF Transmitting Antenna. Science and Technology Innovation and Application, 2022, 12 (03): 59-61.

[14] Lopez A R. Fundamental limitations of small antennas: validation of wheeler’s formulas. IEEE Antennas and Propagation Magazine, 2006, 48 (4): 28-36.

[15] Li Xu. Application Analysis of Big Data Technology in Computer Information Security. China Information Society, 2024, (01): 93-96