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Sensitivity Criterion and Law on a Navigation Receiver under Single Frequency Electromagnetic Radiation

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Abstract: To objectively assess the anti-electromagnetic interference ability of the navigation receiver, the sensitivity criterion of a certain type of navigation receiver is tested under single-frequency continuous wave electromagnetic radiation with an optimized testing method. The experimental results show that it is difficult to guarantee the accuracy of the measurement value of the sensitivity level by using the carrier-to-noise density ratio (C/N0) as the sensitivity criterion, but the initial C/N0 of each satellite can be used as the basis for identifying whether the navigation system has recovered from the interference. The experimental error is dramatically decreased when the sensitivity criterion of "the sensitive phenomenon appears within the first 4 s, and the loss of positioning lasts for 30 s" is employed, the variable interference power step size is adopted and all of the satellites C/N0 are required to recover to the initial value after an interference. The critical interference field intensity error can be controlled within 1 dB by using all these measures. The sensitivity law of the navigation receiver is the same under different working signal intensities. It is significantly sensitive in the working frequency bandwidth. It is also quite sensitive in −11.5 MHz~55.5 MHz of the frequency offset range. The positive sensitive bandwidth is about 5 times that of the negative sensitive bandwidth.

Keywords: navigation receiver; interference mechanism; sensitivity criterion; variable step size; sensitivity law

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1. Introduction

The weak working signal of the navigation system is extremely susceptible to various types of electromagnetic radiation. Therefore, more and more attention is drawn to its anti-jamming performance research. At present, the research on navigation receivers mainly focuses on three aspects. Firstly, the influence of all kinds of electromagnetic interference signals on the performance parameters of commercial navigation receivers [1] is studied, where the C/N0 [2–4], interference rejection level, and interference recovery time [5] are used as effect parameters to evaluate the influence of electromagnetic interference on the performance of navigation receivers. Secondly, anti-interference methods and algorithms [6,7] are proposed to improve the anti-interference performance of navigation receivers by inhibiting interference signals. Finally, the interference prediction models based on the interference mechanism are established by studying the interference prediction methods [8–10]. Whatever the research perspective is, the sensitivity criterion needs to be defined at first. Both the GJB-4405A-2006 [11] and GJB-6741-2009 [12] have defined the assessment rule of the jamming effect for speech communication and digital communication, respectively. The interference to speech and digital communication equipment is divided into five levels for these two. The subjective method is adopted to evaluate the speech signal in the speech communication system, i.e., no interference, very weak interference, weak interference, strong interference, very strong interference, while the objective method of the increment of bit error rate(BER) is employed to assess the digital signal in digital communication system, i.e., $\Delta P_e \leq 1\%$, $1\% < \Delta P_e \leq 5\%$, $5\% < \Delta P_e \leq 7.5\%$, $7.5\% < \Delta P_e \leq 10\%$ and $10\% < \Delta P_e$. The sensitivity criterion of a certain type of communication equipment could be more easily defined based on the above two standards. The sensitivity threshold level testing method in GJB-151B-2013 [13] or MIL-STD-461G [14] could be appropriate for general electronic equipment to obtain the electromagnetic sensitivity threshold. However, the relevant materials on the sensitivity criterion of navigation receivers was not provided in current studies. Meanwhile, the signal intensity of the navigation receiver is relatively weak, and the measurement error is bound to be too large by adopting the conventional measurement methods, which is worthy of further study.

In this context, the electromagnetic interference mechanism of non-linear equipment is analyzed firstly. Furthermore, the sensitivity criterion of equipment in current studies is analyzed to draw the application of the sensitivity criterion on a navigation receiver. After defining the sensitivity criterion of the navigation receiver based on the effect sensitivity phenomenon and establishing the measurement method, which includes the variable interference power step size and the requirement of a system recovery state after each interference, the single-frequency continuous wave electromagnetic radiation effects experiment is carried out on a certain type of navigation receiver. The repeatability and accuracy of the critical interference power/field intensity testing data adopting the proposed measurement method will be validated, and the sensitivity law of the navigation receiver will be explored.

2. Related Works

The existing sensitivity criteria of equipment is usually classified into two categories: objective and subjective methods [15]. Chen et al. [16] believed that an interference margin could be used as the sensitivity criterion for analog communication systems, while BER is always used as the sensitivity criterion for digital communication systems. Li et al. [17] specifically studied the sensitivity criterion of a communication station under single-frequency continuous wave interference. The sensitivity criteria of voice communication and digital communication are defined. In voice communication, the work damage level of communication interruption can be used as the sensitivity criterion, while the error is smaller when adopting 10% BER in digital communication. Qi et al. [18] studied the influence of electromagnetic pulse sequence on digital communication station. In their study, it confirms that it is effective to take the BER as a sensitivity criterion for the digital communication system once again. However, a fixed BER value cannot be taken as the sensitivity criterion in electromagnetic pulse interference. The relationship between BER and the pulse repetition rate could be used as the criterion, which is more suitable for the sensitivity measurement of digital communications. It also demonstrates that the sensitivity criterion should be related to the interference signal type. Zhang et al. [19] carried out a relevant piece of research on an unmanned aerial vehicle data link system. It finally shows that the automatic gain control (AGC) voltage and BER could be used as the sensitivity criteria of the system. Zhao et al. [20] adopted the field intensity amplitude compression value (1.5 dB, 6 dB, and 12 dB) of the echo signal on the tested radar as the sensitivity criterion. In the relevant research on navigation receivers, Zhang et al. [21] defined the sensitivity criterion of a certain type of BeiDou navigation receiver as the C/N0 of 30 dB-Hz on a single-satellite experimental study. Mansson et al. [22] studied the influence of different interference signals on the handheld global positioning system (GPS) receiver. By observing the responsiveness of the receiver in the experiment, it adopts five disparate effect phenomena, i.e., no observed effect, interference while working, loss of positioning then self-recovery, loss of positioning requires human intervention, physical damage as the criterion to show the sensitivity effect of the receiver under various jamming signals' interference.

To sum up, a researcher could use a distinct electromagnetic sensitivity criterion for a different equipment. Sometimes, the sensitivity criterion is not exactly identical even though the tested equipment is the same one. From the analysis, we can see that the definition of sensitivity criteria on a certain tested equipment is related to the type of interference signal and the research purpose. Navigation receivers are more susceptible to continuous wave electromagnetic signal [23]. In additional, continuous wave interference is the most often used one in these interference signals [24]. The C/N0 is primarily used as an objective criterion in studies. However, the critical interference C/N0 of the navigation receiver is unstable. The critical value is tied to the working signal intensity and experiment configuration. There is a challenge to test the critical interference level with a fixed C/N0. If the sensitive phenomenon is taken as a subjective criterion, a further piece of experimental research on how to classify sensitive phenomenon is indispensable. Furthermore, one thing we can determine is that the sensitive phenomenon is varied with the variation of C/N0. From the unresponsiveness of the receiver to total blocking, there may be a zone where part of the signals is blocked. In which, although the satellites are blocked partially, the tested receiver still works when the number of positioning satellites is more than or equal to five other than the four satellites mentioned in the literature. However, regardless of the partial blocking, only two values of positioning altitude in receiver software are used to show the positioning or loss of positioning, which is related to the C/N0 of each satellite and the sensitive phenomenon. As a result, we can get the idea that anti-jamming performance of the navigation receiver could be accurately determined by adopting the measurement method which combines the variation of C/N0 and sensitive phenomenon. The tested receiver is a newly developed piece of equipment which deserves further study.

3. Materials and Methods

3.1. Interference Theory Analysis

Power series expansion [10] is mainly employed for the analysis of non-linear systems. The influence of jamming signals on tested equipment could be analyzed by useful signal gain. Generally, the relationship between the input and output of tested equipment under the electromagnetic radiation can be expressed by the first four terms of the power series expansion, namely Equation (1):

$$u_o = b_0 + b_1 u_i(t) + b_2 u_i^2(t) + b_3 u_i^3(t) \tag{1}$$

where, u_o is the output signal of the receiver, $b_i (i = 1, 2, 3)$ is the non-linear coefficient, and $u_i(t)$ is the input signal of the receiver.

When it is under single electromagnetic radiation, the input signal $u_i(t)$ of the receiver can be denoted as Equation (2):

$$u_i(t) = A_s E_s \cos w_s t + A_i E_i \cos w_i t \tag{2}$$

where, A_s and A_i is the selective coefficient of useful signal and the interference signal of the receiver, respectively, including the antenna coefficient and amplitude–frequency coefficient of the filter in radio frequency (RF) front-end; E_s and E_i is the field intensity of the useful signal and interference signal, separately; ω_s and ω_i is the radian frequency of the useful signal and interference signal, respectively.

By substituting Equation (2) into Equation (1), the fundamental component of the useful working signal and interference signal can be obtained as Equations (3) and (4), separately:

$$x_s = (b_1 A_s E_s + \frac{3}{4} b_3 A_s^3 E_s^3 + \frac{3}{2} b_3 A_s E_s A_i^2 E_i^2) \cos \omega_s t \tag{3}$$

$$x_i = (b_1 A_i E_i + \frac{3}{4} b_3 A_i^3 E_i^3 + \frac{3}{2} b_3 A_i E_i A_s^2 E_s^2) \cos \omega_i t \tag{4}$$

Hence, the useful signal gain under the single-frequency electromagnetic radiation could be obtained from Equation (3). It can be expressed as Equation (5):

$$K_s = b_1 + \frac{3}{4} b_3 A_s^2 E_s^2 + \frac{3}{2} b_3 A_i^2 E_i^2 \tag{5}$$

when the input signal is small, the system works in a linear region, then $K = b_1$. When the input signal is gradually increased to non-linear region that the system works in, the useful signal gain decreases with the increase of the input signal. When $A_s^2 E_s^2 + 2A_i^2 E_i^2 = -\frac{4}{3}\frac{b_1}{b_3}$, then $K = 0$. In this case, the useful signal completely disappears, and the system is interfered by electromagnetic radiation. This is caused by the blocking interference of the RF front-end of the receiver, which could result in the interruption of data transmission. It also shows that the coefficient b_3 is a negative number.

Whether the useful signal or the interference signal is too large, the blocking interference of the RF front-end will be generated. However, the contribution of the interference signal to the useful signal gain reduction is obviously greater than that of the useful signal. The working signal of the navigation system is weak, and this feature is more apparent.

The useful signal gain of multi-frequency interference can be analogized, but there may be a blunt effect [25]. In this case, the fifth order term or even higher order term of power series expansion needs to be taken into account, and its effect phenomenon on navigation receivers deserves careful further study. However, the effect phenomenon must be the reflection of the useful signal gain.

3.2. Sensitivity Phenomenon and Criterion on Navigation Receiver

In studies on navigation receivers, the C/N0 [26,27] is always used as the sensitivity criterion for the satellites' loss of lock. In the test, a certain type of navigation signal simulator is utilized to generate navigation signals, and the transmitting power is set as −90 dBm and −110 dBm, respectively. When 9 satellites are turned on, the initial C/N0 of all satellites is 54 dB-Hz and 50 dB-Hz, separately, which is not proportional to the transmitting signal power. By observing the output data of the satellites' status in receiver software, the C/N0 of each working satellite can be obtained. The receiver could not receive any signal from the satellites when the number of positioning satellites is less than 5. In that case, the C/N0 of each satellite which is losing its positioning is less than 38 dB-Hz under −90 dBm working power and it is less than 34 dB-Hz for −110 dBm working power. Hence, the critical interference C/N0 of each satellite is defined as 38 dB-Hz when the working power is −90 dBm, while the C/N0 needs to be reduced to 34 dB-Hz when the working power is −110 dBm.

Therefore, it is inaccurate to employ a fixed C/N0 value as the sensitivity criterion of the navigation receiver. In this study, the requirement of positioning is that there must be at least 5 positioning satellites for the navigation receiver. During the interference process, the satellite's C/N0 is constantly changing. When the navigation receiver is interfered by single-frequency electromagnetic radiation at a certain frequency, satellites C/N0 may experience the process of "decreasing–jumping–increasing", and the system is still in positioning in the end. Therefore, it is difficult to decide the critical interference state of the navigation receiver only by using the C/N0 as the sensitivity criterion.

By observing the positioning longitude, latitude and altitude in the navigation system software, it is found that the positioning altitude is more sensitive to electromagnetic interference. In our experimental environment, the altitude usually keeps at 66 m without any electromagnetic radiation interference. This value is related to the geographical position of receiver. It is rapidly reduced to 0 m without any intermediate value appearing when the electromagnetic interference reaches a certain level. In this case, the navigation receiver loses its positioning function. It is easier to tell if the system is working properly by using the altitude. Therefore, the positioning altitude is taken as the sensitivity criterion will be helpful to test the accurate sensitivity data.

Each sensitive phenomenon obtained by observing the positioning altitude of the navigation receiver in the experiment is shown in Table 1. In order to define the accurate sensitivity criterion, it is necessary to examine the effect phenomenon so as to ensure the stability of the sensitivity criterion.

Table 1. Electromagnetic interference sensitive phenomena of the navigation receiver.

Level	Interference Effect	Duration of Positioning Loss
Level 1	Loss of positioning flashes once	About 1 s, the phenomenon does not occur at partial frequency
Level 2	Skip between the positioning and loss of positioning	Duration time and jumping frequency are variable
Level 3	Positioning is initially normal and loss of positioning after 5 s	About 10~20 s, then self-recovery
Level 4	Loss of positioning within the first 4 s	Above 30 s, it can be understood as a permanent loss of positioning under interference

As can be seen from Table 1, the loss of positioning duration is different in each phenomenon level. To accurately define the sensitivity criteria, not only must be the navigation receiver be effectively interfered by the minimum power, but also the time parameter is a prerequisite. In phenomenon level 1, the loss of positioning only is shown for a second, which cannot lead to effective interference to the navigation receiver, and even this phenomenon does not occur at some frequency points. Both of the phenomenon level 2 and level 3 have great uncertainties on measurement, the measured threshold of sensitivity is not stable. The measurement of sensitivity according to the first three sensitivity phenomena in Table 1 is extremely unstable, the maximum error is up to 6 dB, which exceeds the acceptable tolerance defined in GJB-151B-2013 [13]. Therefore, the sensitivity criterion was finally defined as "loss of positioning within the first 4 s from the beginning of electromagnetic radiation, and the loss of positioning duration lasts for 30 s". Why in the first 4 s? The option is that once the initial positioning time exceeds 4 s, the positioning can be recovered within 30 s even if the loss of positioning duration could last for a certain time (less than 30 s). Moreover, it also takes into account the interference response time of the navigation receiver in 4 s. With this criterion, the measurement of critical sensitivity level is relatively stable under electromagnetic interference.

3.3. Selection of Interference Power Step Size

According to the measurement method of the sensitivity threshold value in GJB-151B-2013 [13], the interference signals should be reduced by 6 dB when the sensitive phenomenon occurs, then the interference signals should be gradually increased until the sensitive phenomenon occurs again. In the process of gradually increasing the interference signal, if the interference power (the interference signal power will be converted to interference field intensity) is increased with a fixed step size; on the one hand, the measured sensitivity threshold could be skipped because of the too large step size, and on the other hand, too small a step size may result in low measurement efficiency. Consequently, variable step size should be used to adjust the interference power for measurement. The closer to the sensitive threshold, the smaller step size is used. The specific measurement steps according to the variable step size are as follows:

Step 1: Firstly, the interference power should be decreased by 6 dB on the basis of the critical interference power at a previous frequency point to ensure the tested equipment is not interfered with under the decreased power; otherwise, lower it by 6 dB once again, and so on.

Step 2: Let us gradually increase the interference power based on the step size of 2 dB until the sensitive phenomenon occurs, as shown in Table 1. After that, the decibel value of each step size should be decreased by 50%, i.e., 1 dB and 0.5 dB.

Step 3: When the effect phenomenon conforming to the sensitivity criterion occurs, the interference power is reduced by 1 step size; otherwise, the interference power is increased by 1 step size and repeat it several times.

Step 4: When the step size drops to 0.5 dB, the interference power is the critical interference power of this frequency point when the sensitivity phenomenon defined by the sensitivity criterion appears.

3.4. Requirement of Recovery State after Interference

In most of studies, recovery time is involved to evaluate the recovery state of the navigation receiver after each interference. However, the experiment on the navigation receiver shows that the positioning altitude instantly recovers from 0 (loss of positioning) to 66 (positioning) when the interference signal generator is turned off, while the C/N0 needs some time to get back to the normal positioning state. When the working power is −90 dBm, the process of losing positioning under interference and the C/N0 recovery is shown in Figures 1 and 2. Where the variation of C/N0 is shown in Figure 1 when the navigation receiver is interfered with at the working frequency point, Figure 2 illustrates a similar process when the interference frequency offset is 9 MHz. In the experiment, 9 satellites are turned on in the navigation signal simulator. In the Figures, 9 different satellites are denoted as S1 to S9. Each expression of S1 to S9 is corresponding to each satellite number of 1 to 9 in the navigation signal simulator.

From Figures 1 and 2, we can get that the C/N0 of each satellite varies in a consistent way after interference. The initial C/N0 of them is relatively stable. It confirms that all of the satellites could recover to the initial C/N0 after a period of recovery. After an interference, the recovery time at the working frequency point is obviously longer than that at the out-of-band frequency point. The recovery time of the out-of-band interference frequency point is less than 30 s, and the closer it is to the working frequency, the longer the recovery time is. Although a fixed interference recovery time cannot be used as the sensitivity criterion, it is feasible to take the initial C/N0 as the recovery state criterion of the navigation receiver.

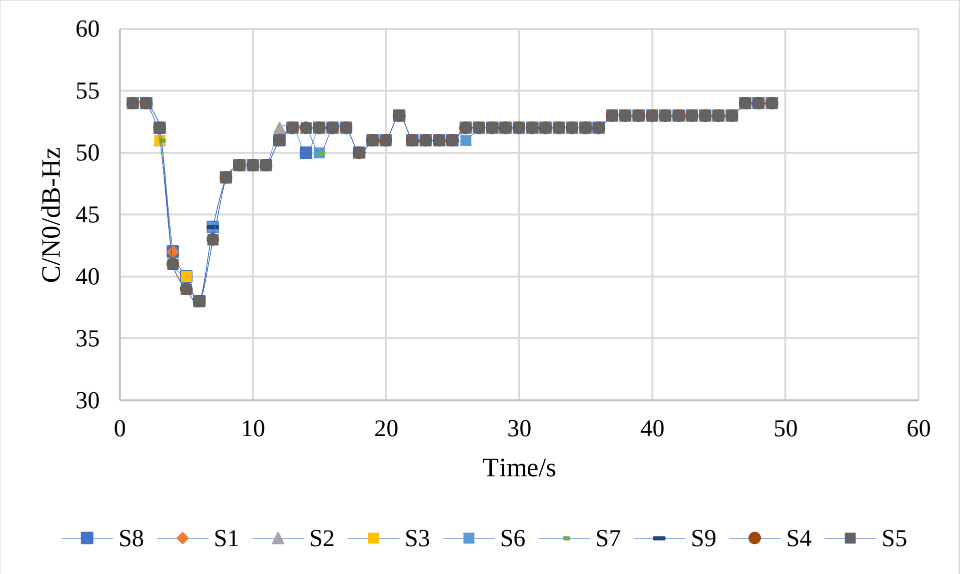

Figure 1. The process of C/N0 recovery when the interference is at working frequency point.

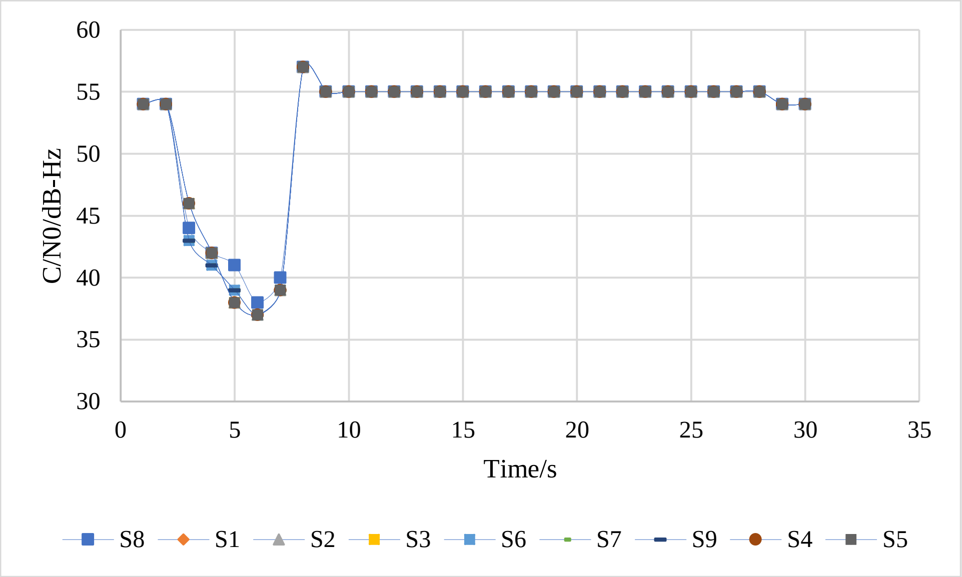

Figure 2. The process of C/N0 recovery when the interference frequency offset is 9 MHz.

4. Experiment and Results

4.1. Experiment Configuration and Preparation

To avoid overly ideal experimental results obtained by the injection method [19], the irradiation method is adopted in this study. Meanwhile, because of the weakness of the navigation system signal and the susceptibility to interference, the near field radiation that is produced by cabinet leakage could remarkably impact the working of the navigation receiver. Hence, except the signal transmitting antenna, receiving antenna and interference antenna, others including the navigation signal simulator, interference signal generator and navigation receiver are placed outside the shielding room. The experiment environment configuration is shown in Figure 3. The specifications and models of the main components in the experimental system are illustrated in Table 2. The signal intensity of the navigation simulator is set by using simulator control software. The working signal is emitted via a broadband horn antenna. An interference signal generator can generate a single-frequency interference signal, which is amplified by 35 dB power amplifier and generates a radiation field through a broadband horn antenna. The special circular polarization receiving antenna for the navigation receiver is used to receive the working signal and interference signal of the system at the same time. The positioning altitude of the receiver and the C/N0 variation of each satellite can be observed through the receiver software. The distance between the transmitting antenna and receiving antenna should be greater than 3 m. The position and angle of each antenna is adjusted so that the navigation receiver works in the most sensitive state. The relative position of each antenna should not be moved. In the experiment, nine satellites of the navigation signal simulator are turned on, and then the output power should be set properly. Next, the navigation receiver is turned on so that the system is in a positioning state. Furthermore, the jamming frequency and power of the signal generator are adjusted to interfere the normal working of the navigation receiver with electromagnetic radiation.

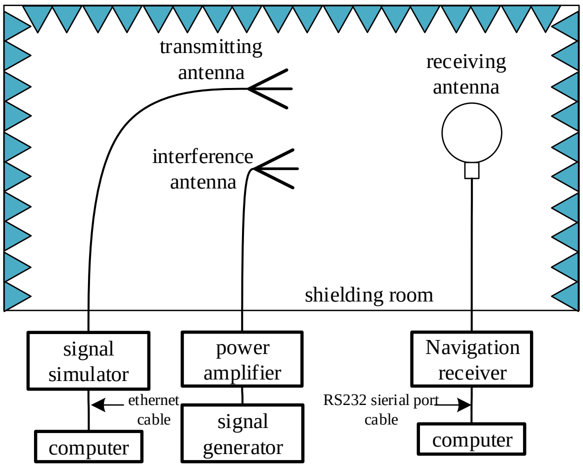

Figure 3. Configuration of sensitivity testing on navigation receiver.

Table 2. The specifications and models of main components in experiment system.

Main Component	Specifications and Models
Signal simulator	CETC-NS8400
Signal generator	RIGOL DSG821 9 kHz−2.1 GHz
Power amplifier	Ceyear 80,224 50 MHz−3 GHz, 35 dB
Navigation receiver	UNICORECOMM UM220
Transmitting/Interference antenna	BBHA9120D 1 GHz-18 GHz
Receiving antenna	Special circular polarization antenna for navigation receiver

4.2. Test Results and Analysis at Typical Frequency Point

The bandwidth of the most sensitive frequency offset of tested navigation receiver is ±2 MHz. Therefore, two different criteria are used to measure the sensitivity twice, respectively, at the typical frequency points within the working bandwidth. The output power of navigation signal simulator is set as −90 dBm and −110 dBm separately. The theory working power of −130 dBm is not selected to test the stability of proposed measurement method because the working state of the navigation system is extremely unstable under this weak power. The signal is emitted by a signal simulator could not be received by the receiver very well when the working power is less than or equal to −120 dBm without any interference.

When the loss of positioning duration is not taken into account, the critical interference power is shown in Table 3. Where measurement 1 and measurement 2 are the two critical interference powers measured at different moments, respectively, which are according to the configuration in Figure 3.

Table 3. Measurement values of critical interference power without regard to loss of positioning duration.

Working Power (dBm)	Interference Frequency Offsets (MHz)	Measurement 1 (dBm)	Measurement 2 (dBm)
−90	−2.5	−40	−39
	−1.5	−41	−40
	−0.5	−43	−41
	0.5	−41	−40
	1.5	−40	−39.5
−110	−2.5	−47	−46
	−1.5	−49.5	−49
	−0.5	−57	−55
	0.5	−53	−50
	1.5	−49	−47

When it takes the "sensitivity phenomenon occurs within the first 4 s and the loss of positioning lasts for 30 s" as the sensitivity criterion, two measurement results at typical frequency points in band are shown in Table 4.

Table 4. Measurement values of critical interference power when the sensitivity criterion is used.

Working Power (dBm)	Interference Frequency Offsets (MHz)	Measurement 1 (dBm)	Measurement 2 (dBm)
−90	−2.5	−37	−38
	−1.5	−38.5	−39
	−0.5	−39	−39.5
	0.5	−38.5	−40
	1.5	−37.5	−38
−110	−2.5	−45.5	−46
	−1.5	−47.5	−47.5
	−0.5	−52	−52.5
	0.5	−49	−49
	1.5	−46.5	−46

From Table 3, we can see that the error of the two measurement results at the same frequency point is up to 3 dB, which indicates that the sensitivity criterion of the navigation receiver is less accurate without regard to the loss of positioning duration. The error between the measured value 1 and value 2 in Table 4 basically remain at about 1 dB. The measured values of critical interference power are all greater than the measured results in Table 3. This conforms to the phenomenon in Table 1. It shows that the sensitivity threshold range of measurement is large when the loss of positioning duration is not taken into account. It also shows the measurement results are unstable once again. However, the results measured by the proposed sensitivity criteria and measurement method are relatively stable.

4.3. Sensitivity Law of Navigation Receiver

The above definition of the sensitivity criterion and the effect experiment method are adopted. Based on the consideration of the stability of the experiment, the critical interference power of the navigation receiver at the working frequency point is measured firstly, then extend to the left and right sides, respectively, when the output power of navigation simulator is −90 dBm and −110 dBm. The position replacement method is used to convert the power to field intensity in the experiment. When the transmitting power P_0 of the signal generator is 29 dBm, the field intensity at the receiving antenna position of the navigation receiver is 5 V/m, that is $E_0 = 14$ dBV/m. Then the critical interference field intensity E at each frequency point can be obtained by $E = E_0 + P - P_0$ (dBV/m) defined in the linear interpolation/extrapolation method [28], where E_0 and P_0 are the reference field intensity and power separately, P is the measurement power for each frequency point. According to the experiment, $E = P - 15$ (dBV/m). The sensitivity curves are shown in Figure 4. To understand the feature of the navigation receiver, the sensitivity curves within the bandwidth of $f_0 \pm 2.5$ MHz in Figure 4 are enlarged. The partial enlarged drawing of it as shown in Figure 5.

When the output signal power of navigation simulator is −90 dBm and −110 dBm, the bandwidths of sensitive interference frequency offset of the tested navigation receiver are −11.5~53.5 MHz and −13.5~55.5 MHz, respectively. Although the stronger the navigation working signal is, the narrower the sensitive interference frequency bandwidth is, the law of variation for the sensitivity of different working signals is always consistent.

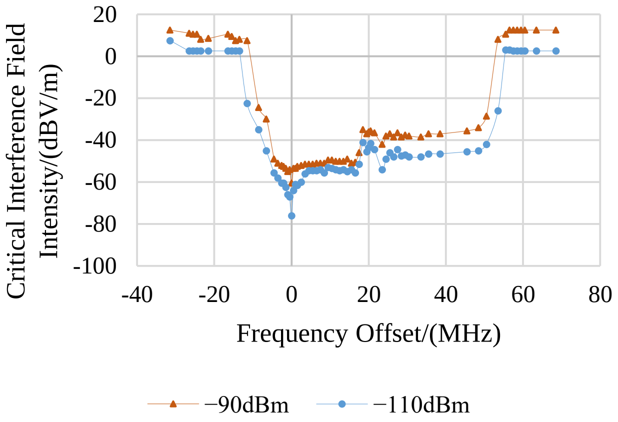

Figure 4. Sensitivity curves of −90 dBm and −110 dBm working power.

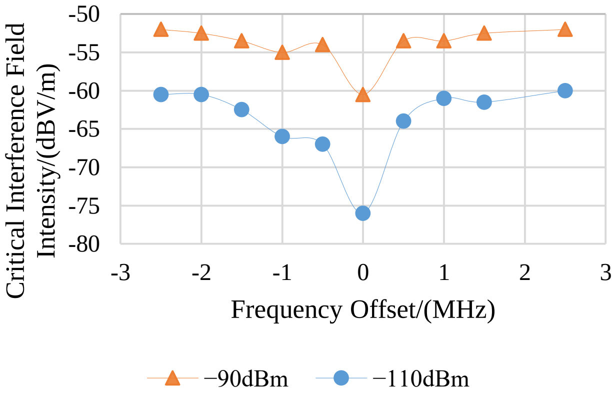

Figure 5. Sensitivity curves of in band.

The working frequency bandwidth of the tested navigation receiver is within the frequency offset of ±2 MHz. In reality, the working frequency point measured in the experiment deviates from the nominal working frequency point, with a deviation value of about 0.4 MHz. Although it is related to the characteristics of the front-end filter of the tested navigation receiver, it is still within the nominal working frequency bandwidth.

The anti-jamming performance of the tested navigation receiver is directly proportional to the working signal intensity of the system. The stronger the working power of the system is, the higher the critical interference field intensity of each frequency point is. It indicates that the anti-jamming ability will be stronger with the decrease in the sensitivity of the navigation receiver.

5. Discussion

5.1. Analysis of Sensitivity Law on Navigation Receiver

Although the working frequency point of the navigation receiver measured by the proposed sensitivity criterion and measurement method deviates from its standard working frequency point, the deviation is not significant, which is consistent with the results of sensitivity studies of other equipment involved in the previous relevant literature [20,21]. The obtained critical interference threshold curve is not completely consistent with the sensitivity law of the general tested equipment. In most of the sensitivity studies, there is only one sensitive frequency band. However, the tested navigation receiver is an exception. The sensitivity curves of the tested navigation receiver in this study present two U-shaped sensitive frequency bands: a working frequency band which is extremely sensitive to electromagnetic radiation, namely, the first sensitive frequency band, and another wider sensitive frequency band including the working frequency band, namely, the second sensitive frequency band. The bandwidth of the second sensitive frequency band is about

10 times that of the first sensitive frequency band. Except to the first sensitive frequency band, the second sensitive frequency band on each of the sensitive curves shows two steps in general, where the sensitive threshold on the right side of the second sensitive frequency band is higher than that on the left side. This is a unique sensitivity law of the tested navigation receiver in this study. Multiple sensitive frequency bands also appeared in a previous relevant study [9], which is considered to be the influence of the internal mixing and crystal space radiation on the receiver. Meanwhile, its multiple sensitive frequency bands are all narrow and they appear symmetrically on the left and right sides of the working frequency point. However, in this study, the sensitive frequency band is wider than the result in previous study and mainly appears on the positive frequency offset side. The special sensitive phenomenon may be due to the pass-band design of the RF front-end filter. Yet, this design is harmful for anti-jamming because of the wide sensitive frequency band. If we realize that it intends to provide a backup of the working band, there is no transition band here. The internal chips of the tested navigation receiver are highly integrated. Although the sensitive bandwidth design intention of the tested navigation receiver cannot be explained more reasonably in this study, the unique sensitive law of the tested navigation receiver found in this study is of great significance to its subsequent research, especially for effect prediction research.

5.2. Limitations

The tested subject in this study is a certain type of navigation receiver, and it is uncertain whether for other types of navigation receiver the proposed sensitivity criterion can be immediately applied. However, the sensitivity criterion based on the sensitive phenomenon level could be taken as a reference for the definition of the sensitivity criterion on other types of navigation receivers. Compared with the direct use of C/N0 as a sensitivity criterion in the previous literature, the subjective sensitivity criterion proposed in this study can be used to accurately assess whether the navigation receiver is effectively interfered. In the experiment, the measured sensitivity data is relatively stable, but the C/N0 should be required to recover to the initial positioning state before you enter into the next accurate sensitivity measurement.

The purpose of this study is to measure the critical interference threshold of a navigation receiver under the interference of single-frequency continuous wave electromagnetic radiation. The critical sensitivity will be used in the prediction model of electromagnetic radiation interference. Therefore, in this study, only single-frequency continuous wave is used to carry out the irradiation experiment on the tested navigation receiver. However, it is still uncertain whether the effect phenomenon is consistent with the results in this study when the tested equipment is interfered with various other types of electromagnetic radiation interference or the injection method is adopted in the experiment. We have emphasized that the tested equipment is more sensitive for single-frequency continuous wave in before section. Hence, even if the tested result in other electromagnetic environments is not completely consistent with our study, the critical threshold may be greater than our experiment result for each frequency point.

6. Conclusions

In order to obtain the accurate critical interference threshold value of a certain navigation receiver at a specific frequency point, we must understand its anti-jamming performance, and prepare for further electromagnetic environmental effect prediction research. The sensitivity criterion is defined based on the sensitivity phenomenon levels of the navigation receiver. The sensitivity measurement method is established according to the overall consideration of C/N0 recovery requirements and the working signal feature of the navigation receiver. The accuracy of the sensitivity threshold can be improved with the proposed sensitivity criterion and measurement method. The experimental results of the single-frequency continuous wave effect on the tested navigation receiver show that:

The initial C/N0 of each satellite is identical under the same working signal intensity, while it is distinct when the navigation receiver works at a different signal intensity. The critical interference C/N0 is also different when the tested navigation receiver is in a different electromagnetic radiation intensity. Although a fixed C/N0 is taken as the sensitivity criterion which will lead to an increase of measurement error, the initial fixed C/N0 still can be used as the reference to evaluate whether the system gets back to the normal positioning state after the jamming is turned off.

The sensitive phenomenon which is caused by electromagnetic radiation of the tested navigation receiver can be classified into four levels. The "loss of the positioning within first 4 s and the duration lasts for 30 s" is taken as the sensitivity criterion, the strategy of variable step size is employed to gradually increase the interference power at each frequency point, and the system recovery state is required to ensure the measurement accuracy and efficiency.

The interference of the navigation receiver mainly comes from the blocking interference of the RF front-end, and its anti-jamming performance is proportional to the intensity of the useful signal. The stronger the useful signal is, the narrower the sensitive bandwidth is, while the higher the critical interference field intensity of each frequency point is, the stronger the anti-interference ability is. The curves of critical interference field intensity are almost the same pattern under different working signal intensities. The positive frequency offset sensitive bandwidth is about 5 times that of the negative frequency offset, which shows that the stronger anti-interference capability in the negative frequency offset.

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