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An Improved Polar-Coordinate Navigation System with the Establishment of Electronic Counter-counter Measures Capabilities

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ABSTRACT

With easy-to-be-disposed architecture and premium navigation performances, polar-coordinate navigation system (PCNS) is still widely utilized by modern military navigation systems. Unfortunately, PCNS has very poor electronic counter-counter measures (ECCM) performances, due to the lack of electronic warfare (EW) considerations during its initial system design. To solve this problem, an improved PCNS (Imp-PCNS) is proposed in this paper to introduce ECCM capabilities to PCNS. The low probability of intercept (LPI) waveforms are utilized instead of regular pulses to reduce the probability of hostile interception. Both the bandwidth and the transmitted power of LPI are designed to generate the signals submerged under the thermal noises at the front ends of enemy receivers. Finally, a kinematic bearing method is proposed to dramatically reduce the possibility of intercept. The principle of kinematic bearing is analyzed in detail. An undistorted observed geometric position (OGP), which is independent of the deviation of observing angle, is achieved by controlling the rotation of the antenna array of PCNS beacon.

Key words: Polar-coordinate navigation system, electronic counter-counter measures, observed geometric position

1. INTRODUCTION

The history of polar-coordinate navigation system (PCNS) can retrospect to the aircraft carrier near-range navigation systems of the U. S. navy in the 40s of last century. One of the well-known PCNS is tactical air navigation (TACAN)[1], which is extensively used by allied and third world military aircraft[2]. Although U. S. Department of Defense (DOD) plans to phase out land-based TACAN in the early years of this century [3], modern PCNS is now widely deployed through out the world with such prestigious users as the U. S. Air Force, North Atlantic Treaty Organization (NATO) and key Airforces in Europe, Middle and Far East, due to its superb reliability and the low cost of ownership[4]. Several navies around the world also use Modern TACAN systems[4].

Unfortunately, very little considerations of electronic counter-counter measures (ECCM) have been taken during the initial design of PCNS, leading to its poor anti-interception performances. When PCNS airborne transreceiver is trying to derive the relative slant-range between the beacon and itself, a couple of pulses, known as the distance-measuring interrogation signal, is transmitted to perform the Secondary Radar Ranging (SRR). Ironically, the usage of this interrogation signal will expose the position of airplane to the hostile surveillances, which is extremely hazardous in wartime. Furthermore, to support the bearing capacity, PCNS beacon needs to transmit a number of dense pulses, which can also be easily intercepted by even a traditional electronic war (EW) receiver. Because modern electronic systems face serious threats from electronic attack (EA) and anti radiation missiles (ARMs)[5,6], it is now well established that, a military system without ECCM capabilities has little possibility to survive in modern warfare[7,8]. The polar-coordinate positioning of PCNS is indeed out-of-date in modern EW. This paper, proposes a new PCNS scheme with the establishment of ECCM capabilities. In order to facilitate the two-dimensional time-frequency search of distance-measuring and also to lower the possibility of intercept, three kinds of low probability of intercept (LPI) waveforms are utilized instead of the pulse waveforms at different stages of distance-measuring. A kinematic bearing method is utilized instead of traditional envelope modulation method. The whole bearing process is conducted without disposing the geometric position of PCNS beacon to hostile detection.

2. THE ECCM DEFICIENCIES OF PCNS

The principle of PCNS is to supply the users with the information of relative slant-range and relative azimuth angle to derive the relative position between users and the beacon. So two basic functions of PCNS are distance-measuring and bearing. During the distance-measuring and bearing processes, both the airplane transreceiver and PCNS beacon need to transmit electromagnetic signals. And it is the transmission of these signals that will induce serious drawbacks to ECCM performances of PCNS. To illustrate this problem in a more clear manner, the ECM threats faced both by the user and PCNS beacon will be addressed in the following parts of this section.

2.1 The ECM Threats Faced by PCNS Users

Since SRR is used in PCNS distance-measuring process, the distance-measuring interrogation signal (i.e., the twin-

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pulses) is needed to be transmitted by PCNS user, leading to a poor electromagnetic-silence for the user. Usually, the same baseband waveform and a fixed carrier frequency are utilized by the distance-measuring interrogation signals for a specific PCNS during single working process, leading to a poor immunity to an off-the-shelf EW receiver. To further illustrate this problem, an example of TACAN distance-measuring interrogation signal is taken herein. The baseband waveform of TACAN distance-measuring interrogation signal is shown in Fig. 1. Because the instant bandwidth is relatively narrow (i.e., 1 MHz) and the carrier frequency is fixed during the whole distance-measuring process, this kind of signal can even be intercepted by a traditional EM receiver, not to mention a high-sensitive modern EM receiver. Once the interrogation signals are intercepted by the hostile receivers, a number of hazards may be faced by TACAN users, e.g., the exposure of user's geometric position to the hostile passive radar system, the attack of surface-to-air or air-to-air anti-radiation missile, and the oppressive or deceptive jamming from enemy's electronic jammers, etc.

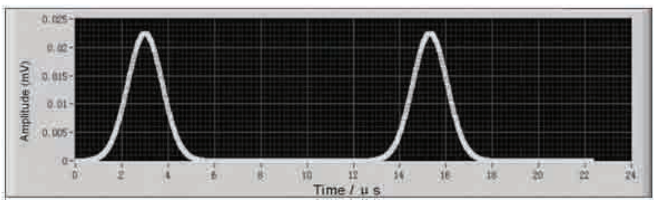


Figure 1. The distance-measuring interrogation signal of PCNS airborne transreceiver.

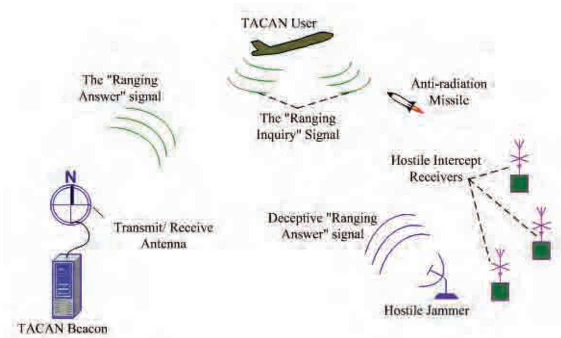


Figure 2. The ECCM hazards of PCNS user (subject to the hostile passive positioning).

2.2 The ECM Threats Faced by PCNS Beacon

During the measurement of relative azimuth angle between the user and PCNS beacon (i.e., the bearing process), the number of pulses transmitted by PCNS beacon must be large enough during a given time duration as shown in Fig. 3 to supply an continuous envelope for bearing, e.g., the TACAN signal consists of 2700 pulse-pairs/second whose amplitude is modulated by a 15 Hz signal and a 135 Hz signal as shown in Fig. 4. Also, the power of transmitted signals must be large enough to provide a precise bearing. These signals can be easily intercepted by an EW receiver. In this point of view, PCNS beacon has very poor ECCM performances. It will subject to a number of attacks, such as anti-radiation missile (ARM) as shown in Fig. 5.

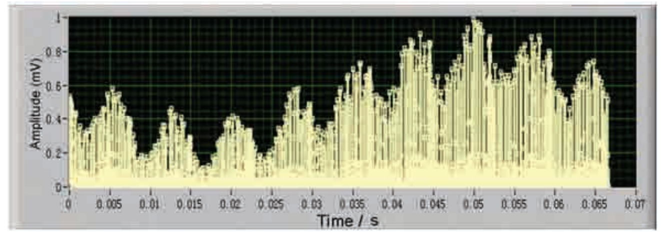


Figure 3. The transmit signals of PCNS beacon.

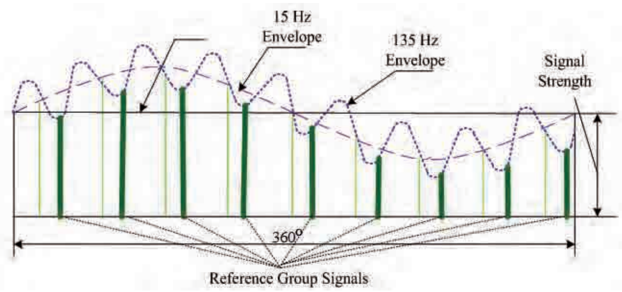


Figure 4. The transmit signals of PCNS beacon for bearing.

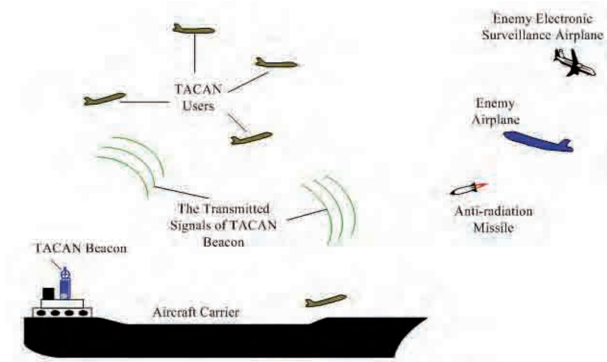


Figure 5. The ECCM hazards of PCNS beacon (subject to the attack of ARM).

3. THE DEVELOPMENT OF PCNS SRR WITH ECCM CAPABILITY

As illustrated earlier, PCNS has very poor ECCM performances during the distance-measuring process. Since the ECCM deficiency of the distance-measuring is caused by the usage of easy-to-be-intercepted pulse waveforms, one effective method to improve the ECCM performance is to use LPI waveforms instead of pulse waveforms. The regular LPI waveforms include: Binary phase shift keying (BPSK) , frequency modulated continuous wave (FMCW), Polyphase Codes (P4, P3, P2 P1 and Frank Codes), Costas Codes, frequency hopping (FH), frequency shift keying and phase shift keying (FSK/PSK)[9-11]. There are also other kinds of LPI waveforms, such as orthogonal frequency division multiplexing (OFDM) and pseudo-random noise waveforms. Generally, the LFM waveform has a relatively bigger possibility of intercept[12], whereas the random noise waveform has a relatively smaller possibility of intercept. Although some of LPI signals may be intercepted by modern receiver techniques[13], the usage of random noise waveform with low peak power can result in very low signal-to-noise ratio (SNR) at enemy surveillance equipment without having access to the transmitted noise waveform[14,15]. Therefore, the ECCM capability of PCNS SRR can be easily improved by utilizing different LPI waveforms during different distance-measuring stages.

4. THE DEVELOPMENT OF PCNS BEARING WITH ECCM CAPABILITY

To resolve the problem of electronic exposure of PCNS beacon, a new bearing scheme, called kinematic bearing, are proposed. LPI waveforms instead of the direction measuring signals are transmitted during the whole process of bearing. The basic signal model of this new bearing method is presented as follows.

$$\chi(y,z)=\int_{y_L}^{y_U}\int_{z_L}^{z_U}\exp\left(\begin{array}{c}\left\{-j\frac{4\pi}{\lambda}\sqrt{y_{bc}^{2}+\left(z-z_{bc}+y_{bc}\tan\varphi_{QX}\right)^{2}}\right\}\\ \delta_{QX}\left(z-z_{bc}+y_{bc}\tan\varphi_{QX},y_{bc}\right)\end{array}\right)$$
$$\bullet\text{sinc}\left(\begin{array}{c}\left[\pi B_t\left(y-2\sqrt{y_{bc}^{2}+\left(z-z_{bc}+y_{bc}\tan\varphi_{QX}\right)^{2}}\right)\right]\\ \varepsilon\left(y_{bc},z\right)dz_{bc}dy_{bc}\end{array}\right)$$
$$\triangleq\int_{y_L}^{y_U}g_1\left(y,z;y_{bc}\right)\otimes_z\varepsilon\left(y_{bc},z\right)dy_{bc}\qquad(1)$$

where y and z are the two-dimensional observed coordinates of PCNS beacon, y_{bc} and z_{bc} are the real coordinates of PCNS beacon. y_L and y_U are the lower bound and upper bound of y_{bc}, respectively, z_L and z_U are the lower bound and upper bound of z_{bc}, respectively, $j=\sqrt{-1}$, λ denotes the carrier wavelength, B_t is the bandwidth of LPI signal, φ_{QX} is the squint angle with respect to the beacon, sinc(x)=sin(πx)/(πx).

$$\delta_{QX}\left(z,y\right)=\begin{cases}1 & \tan^{-1}\left(\varphi_{QX}-\frac{\theta_{beam}}{2}\right)\le\frac{y}{z}\le\tan^{-1}\left(\varphi_{QX}+\frac{\theta_{beam}}{2}\right)\\ 0 & \text{otherwise}\end{cases}\qquad(2)$$

denotes the beamwidth of the receive antenna of PCNS user. The first term of the integrand in represents the phase caused by one-way transmit delay of PCNS signal; the second term represents the restriction of user observing angle due to the limited receive antenna beamwidth; the third term refers to the pulse compression result of LPI; the forth term (namely, $\varepsilon(y,z)$) is the geometric position function (GPF) of PCNS beacon. Therefore, it represents that the received signal of PCNS user is the combination of all the arriving signals transmitted by the beacon.

The derivation of the observed geometric position (OGP) of PCNS beacon is discussed in the following. As shown in Eqn. (1), the bearing reply signals can be deemed as the convolution of the GPF with LPI waveform. In order to solve the GPF from the integral equation, the two-dimensional frequency spectrum of the bearing reply signals is deduced in this subsection. The Fourier Transform (FT) of Eqn. (1) with respect to y can be expressed as

$$X\left(\xi_y,z\right)=\int_{y_L}^{y_U}G_1\left(\xi_y,z;y_{bc}\right)\otimes_z\varepsilon\left(y_{bc},z\right)dy_{bc}\qquad(3)$$

where $G_1(\xi_y, z; y_{bc})$ is the FT of $g_1(y, z; y_{bc})$ with respect to y. Also, the FT of (3) with respect to z can be derived as

$$X\left(\xi_y,\xi_z\right)=\int_{y_L}^{y_U}\hat{G}_1\left(\xi_y,\xi_z;y_{bc}\right)\bullet\varepsilon\left(y_{bc},\xi_z\right)dy_{bc}\qquad(4)$$

where, $\hat{G}_1\left(\xi_z,\xi_y,y_{bc}\right)$ and $\varepsilon(y_{bc},\xi_z)$ are the FTs of $G_1(\xi_y, z; y_{bc})$ and $\varepsilon(y_{bc}, z)$, respectively. In practical application, $\chi(y, z)$ in (1) can be derived directly from the received signals of PCNS user, so $X(\xi_z,\xi_y)$ in Eqn. (4) can indeed be pre-known. The difficulty of solving $\varepsilon(y_{bc},\xi_z)$ lies in the influence of $\hat{G}_1\left(\xi_z,\xi_y,y_{bc}\right)$ which can also be expressed as

$$\hat{G}_1\left(\xi_z,\xi_y,y_{bc}\right)=\text{rect}\left(\frac{\xi_y}{B_t}\right)B_t^{-1}\int_{z_L}^{z_U}\delta_{QX}\left(y_{bc},z+y_{bc}\tan\varphi_{QX}\right)$$
$$\times\exp\left\{-j\frac{4\pi}{\lambda}\sqrt{y_{bc}^{2}+\left(z+y_{bc}\tan\varphi_{QX}\right)^{2}}\right\}\exp\left\{-j2\pi z\xi_z\right\}dz\qquad(5)$$

where

$$\delta_{QX}\left(y,z\right)=\begin{cases}1 & \tan^{-1}\left(\frac{\pi}{2}-\varphi_{QX}-\frac{\Phi}{2}\right)\le\frac{z}{y}\le\tan^{-1}\left(\frac{\pi}{2}-\varphi_{QX}+\frac{\Phi}{2}\right)\\ 0 & \text{otherwise}\end{cases}\qquad(6)$$

According to FT properties that convolution in time domain is equivalent to multiplication in frequency domain, can be expressed in another form as

$$X\left(\xi_y,\xi_z\right)=\text{IFT}\left\{\hat{G}_1\left(\xi_y,\xi_z;\xi_{y_{bc}}\right)\bullet\varepsilon\left(\xi_{y_{bc}},\xi_z\right)\right\}\qquad(7)$$

where IFT{•} denotes Inverse Fourier Transform (IFT). Therefore, it has the following relationship expressed as

$$\varepsilon\left(\xi_{y_{bc}},\xi_z\right)=\hat{G}_1^{-1}\left(\xi_y,\xi_z;\xi_{y_{bc}}\right)\bullet\text{FT}\left[X\left(\xi_y,\xi_z\right)\right]\qquad(8)$$

where FT[•] denotes FT. Obviously, $\varepsilon(y_{bc},z_{bc})$ can be derived from the two-dimensional IFT of Eqn. (8), *i.e.*, we have obtained the GPF of PCNS beacon and the relative azimuth angle can then be derived.

- The airplane induced relative-motion

If the beacon's antenna array is stationary during the bearing process, then the change of observing angle is caused only by the motion of airplane. This will bring convenience to the PCNS beacon design, because no servo is needed to rotate the antenna array. However, the observed geometric position (OGP) of PCNS beacon will be distorted by the non-orthogonal observing angle, because the change of observing angle will decrease. In fact, the more the absolute value of the observing angle is deviated from 90 deg, the more severely the OGP will be distorted.

- The beacon induced relative-motion

To solve the problem of OGP distortion, the beacon antenna array needs to be rotated either by electronic sweep or by mechanical servo as shown in Fig. 6. In this circumstance, the change of viewing angle is mainly induced by the rotation of beacon antenna array, and the effect of OGP distortion caused by non-orthogonal observing angle can be ignored. In fact, a rotation rate of 5 round/min is sufficient to provide the needed variation of viewing angle.

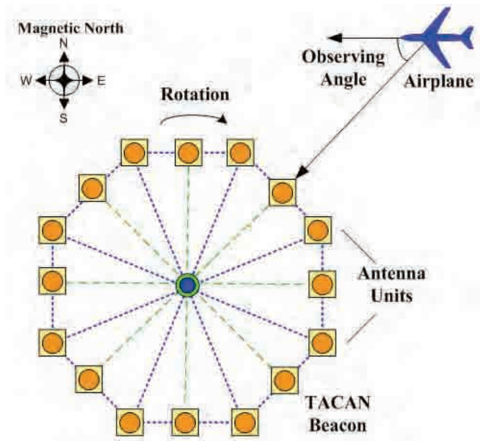


Figure 6. The geometric relationship of beacon induced relative-motion.

5. NUMERICAL SIMULATION AND ANALYSIS

Numerical simulations are conducted in this section to further illustrate the performances of Imp-PCNS. The parameters of simulation are listed as follows: carrier frequency: 1.15 GHz, bandwidth: 10 MHz, pulse width: 1 ms, receiver sampling rate: 35 M samples/s, SNR: -30 dB. The velocity of airplane is 350 m/s. The relative azimuth angle of airplane with respect to PCNS beacon is 135 deg. The antenna array radiuses of PCNS beacon are 30 m and 3 m for airplane induced relative-motion and beacon induced relative-motion, respectively. The rotation rate of the antenna array is 2.5 round/min for beacon induced relative-motion. Firstly, the performances of airplane induced relative-motion are simulated. And its OGPs with different deviation angles are shown in Figs. 7 through 9. It can be seen that a 45 deg deviation of the observing angle will

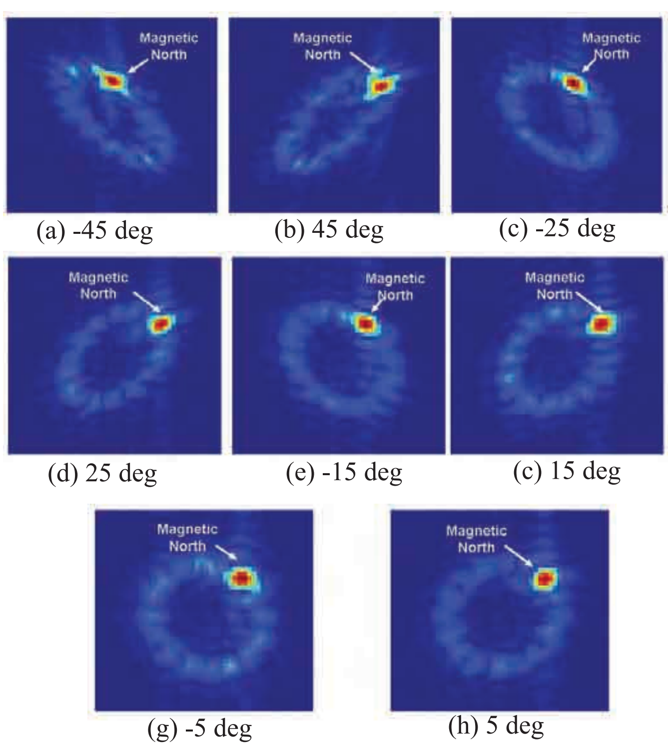


Figure 7. The OGP of PCNS beacon with different deviation angles (bandwidth: 150 MHz).

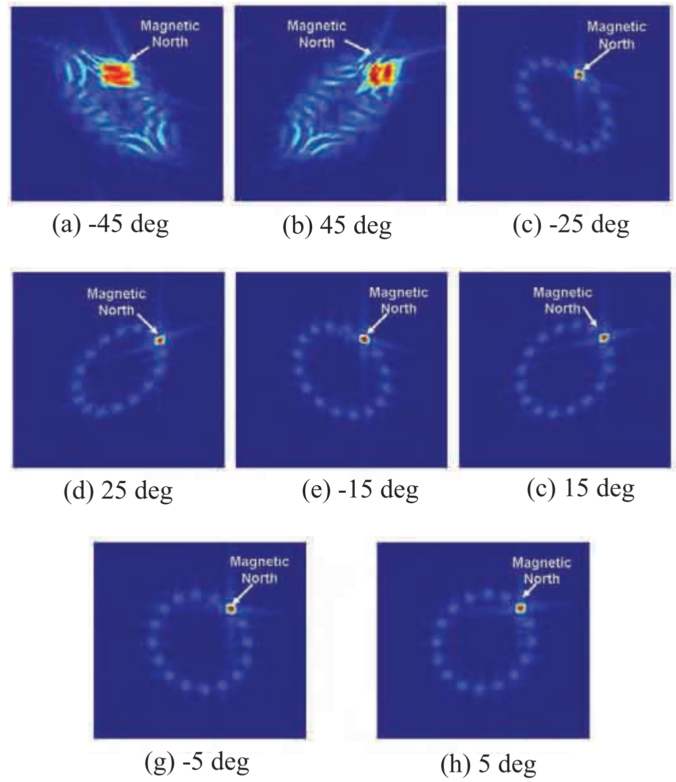


Figure 8. The OGP of PCNS beacon with different deviation angles (bandwidth: 300 MHz).

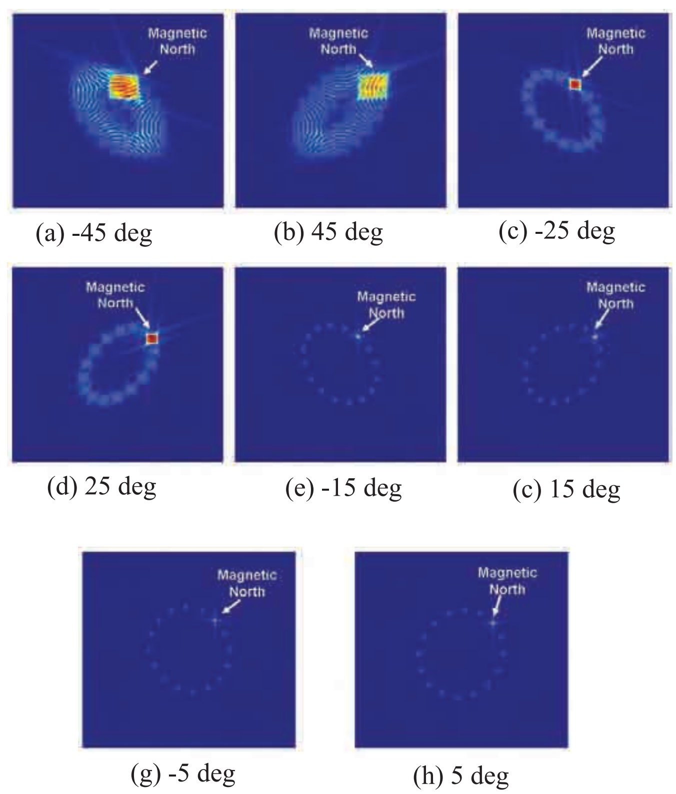
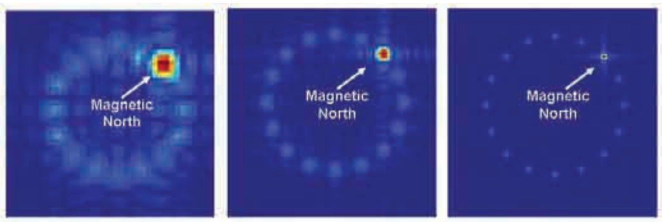


Figure 9. The OGP of PCNS beacon with different deviation angles (bandwidth: 750 MHz).

distort the OGP to an unacceptable extent. And the deviation angle with opposite sign will introduce a distortion of the same volume but in the opposite direction. Moreover, it can be seen by comparing Figs. 7, 8, and 9, in order to alleviate the influence of non-orthogonal observing angle, a wider bandwidth of LPI signal is needed for airplane induced relative-motion. Secondly, the deviation angle is set to be 90. The performances of beacon induced relative-motion are simulated, and their results with different bandwidths are shown in Fig. 10. It can be deduced that, the deviation of observing angle has no influence on the OGP for beacon induced relative-motion.



(a) 150 MH_Z (b) 300 MH_Z (c) 750 MH_Z

Figure 10. The OGP of PCNS beacon with different bandwidths (beacon –induced motion).

6. CONCLUSION

Compared with traditional PCNS, the introduction of LPI waveforms has promised a much better ECCM performance for Imp-PCNS to work in modern electronic warfare. The biggest ECCM difficulty of PCNS lies in the bearing process, where large transmit power and dense pulses are needed by beacon to provide a continuous and clear envelope. Although the bearing capacity seems the same for both PCNS and Imp-PCNS, the latter has a fundamentally different principle to derive the relative azimuth angle. When the change of observing angle is caused by the relative motion of airplane, the observed GPF of PCNS beacon will be distorted by the non-orthogonal observing angle. By rotating the antenna array of the beacon either mechanically or electronically, the distortion of GPF can then be greatly alleviated under the condition of non-orthogonal observing angle.

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