The Receiving Antenna Mode of Troposcatter Passive Ranging Based on the Signal Group Delay

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Complete List of Authors:	WANG, Zhuang; ATR Laboratory, Wang, Mengnan; National University of Defense Technology, ATR Laboratory; Wang, Qi; National University of Defense Technology, ATR Laboratory Cheng, Zhu Zhang, Xueting; National University of Defense Technology, College of Information System and Management
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The Receiving Antenna Mode of Troposcatter Passive Ranging Based on the Signal Group Delay

Zhuang Wang [1], Mengnan Wang [1*], Qi Wang [1], Zhu Cheng [2], Xueting Zhang [3]

[1] ATR Laboratory, National University of Defense Technology, Changsha, China.
[2] College of Electronic Science and Engineering, NUDT, Changsha, China.
[3] College of Information Systems and Management, NUDT, Changsha, China.
*wangmengnan121 @sina.com

Abstract: The Beyond-Line-of-Sight (BLOS) ranging of radiation sources can be realized through the troposcatter propagation of electromagnetic (EM) signals. Present troposcatter ranging systems are based on multi-station cross localization theory wherein synchronization and data fusion of all stations are not tractable. The troposcatter signal group delay properties provide a new ranging mechanism that can be realized through a single station conveniently and inexpensively. However, for radiation sources with multibeams e.g. frequency-scanned radar, which forms several sub-beams with different elevation angles in the vertical direction, the scattering signal of sub-beams with high elevation angles has overall hysteresis compared to lower ones. This effect is called group delay between sub-beams. In this study, a one-to-one correspondence between group delay and target distance is derived to a closed-form expression with target and receiver antenna parameters. Furthermore, a group-delay-based passive ranging mechanism is proposed for exploiting this correspondence to increase the range of the BLOS target. Then two indicators for evaluation, ranging resolution and delay-measure requirement, are proposed for investigating ranging performance under the receiving antenna mode with different elevation angles, vertical beamwidths and erection heights. Results show the ranging resolution is approximately 0.1~0.3 $\left(\mu s / 300 km\right)$ and delay-measure requirement is approximately 0.002~0.033 μs for the given parameters.

1. Introduction

The troposcatter phenomenon was discovered in the 1930s and has been in practice since the 1950s; subsequently a large number of troposcatter communication systems were built in North America, the North Atlantic, the Mediterranean, the West Pacific and Southeast Asia. In the 1980s, after the International Radio Consultative Committee (CCIR) issued a global troposcatter database[1], the International Telecommunication Union Radio communication part (ITU-R) put forward many suggestions such as P.452[2], P.528[3], P.617[4], P.1546[5] etc. A statistical prediction method of troposcatter propagation loss adapted to global application is raised by Zhang Minggao in [6], which lays the foundation of CCIR238-6 mode [7] and P.617-3 recommendation [4]. With the above materials, we can analyse the characteristics of troposcatter very well. In addition, some recent works about the troposcatter transmitting attenuation [8] and its power delay spectrum properties [9] are also inspired. As to the existing passive ranging system based on troposcatter propagation mechanism, KOLCHUGA the Electronic warfare Support Measures (ESM) system [10] was developed by Ukraine comprising two or more sites, deployed tens of kilometres apart to locate emitters by triangulation with a working band of 100 MHz to 18 GHz; SDD electromagnetic signal monitoring system developed by Czech Republic [11] realizes the radio-electronic signals target azimuth detection by single station system, and target position detection by multi-station cross position with a working frequency band of 0.8 GHz to 8 GHz.

Currently, existing troposcatter ranging mechanisms usually have to fuse multi-station information to range BLOS targets such as in [12] and to track them as discussed in [13], or to synthesize racetrack information of an airborne station to range and track targets as in [14]. Consequently, a single ground base station position system is of significant value to troposcatter BLOS ranging with its potential convenience (which may be built on vehicles) and reduced expense. Due to the large range distribution of the scatterers, which are the re-radiated sources of the incoming target's transmitting signals, the arrival time of target transmitting signal properties change with distance, whether this relationship can be used to realize single station position is the key content of this paper. Large or medium-sized ships are widely equipped with frequency-scanned early warning radar [15], which will form several sub-beams, with different elevation angles in the vertical space of the transmitting beam, in a very short time. On account of the troposcatter effects, high elevation beams have a group delay compared to the low elevation beams due to the overall hysteresis when reaching the receiving antenna. Additionally, the group delay has one-to-one correspondence to the target distance provided that the parameters of transmitting and receiving antennas are fixed. Therefore, by seeking a diminished effect of the group delay of a multi-beam emitter, than in conventional work, we propose a troposcatter passive ranging mechanism based on signal group delay which may be applied to detect and range signals with pulsed and continuous waves of practically all known radio technical equipment (RTE) deployed on ground, sea and air platforms, including radar units of all classes, identification systems, air traffic control system and navigation systems as long as the equipment emits multi-beams in an elevated direction. The main contribution of this work is three-fold. First, a troposcatter passive ranging mechanism, based on signal group delay, is derived with an assumed target as the frequency-scanned radar. Second, ranging resolution and delay-measure requirement are proposed as the ranging performance evaluation indicators, and the performance is evaluated under receiving antenna mode of different elevation angles, vertical beamwidth and election height. Third, the performance deterioration under troposcatter multipath fading is considered to meet practical propagation scenarios.

The remainder of this paper is organized as follows. The frequency-scanned radar is taken as an example of a detection target, the delay spectrum and power loss among several sub-beams of troposcatter target signals are analysed in vertical space and the proposed ranging mechanism is derived with appropriate antenna parameters in Section 2. Then the ranging performance is studied corresponding to different receiving antenna elevations, the beam width of elevation angle and the antenna height of single station passive ranging system in Section 3. The influence of multipath fading due to the troposcatter propagation impairments is considered in Section 4. The conclusion is reached in Section 5.

2. Passive Ranging Mechanism Based on Group Delay of Troposcatter Signal

2.1. The Beam Scanning Pattern of Frequency-Scanned Radar

For frequency-scanned radar with an electronically programmed elevation scanning mechanism, which is commonly deployed in sea platforms, several sub-pulses are transmitted during a pulse period. These sub-pulses include a range of frequencies to form different elevation sub-beams in vertical space and contribute to the frequency dispersion characteristics of the feedback network. These sub-beams may overlap or be distributed within an elevation angle range, and reside in the vertical space for a certain period of time according to the operation mode, after which, they change to another vertical space from the original one through frequency scanning technology, until the traversal of all vertical spaces is obtained.

As is shown in Figure 1(a), the transmitter emits electromagnetic signals during a pulse period with three frequencies, which form three sub-beams in vertical space through the antenna radiation as Sub-Beam 1, Sub-Beam 2 and Sub-Beam 3 as shown in Figure 1(b). Therefore, elevation angles of the sub-beams are determined by the transmitting frequency. Since some of the widely used frequency-scanned radar on sea platforms are working in E/F band (the same as S band) as in [15], without loss of generosity, the target EM signal is assumed to be in S band around 3 GHz.

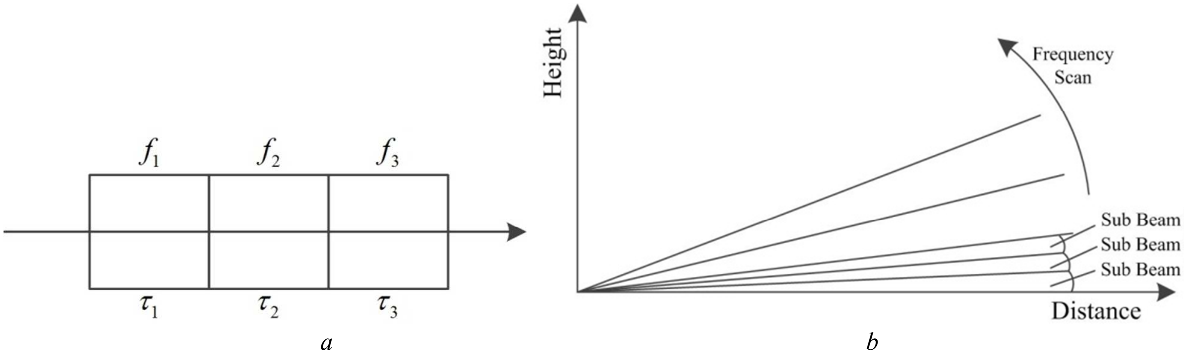


Fig. 1.*The beam scan of intra pulse frequency-scanned radar*
a The wave of transmitting pulse
b The beam diagram sub-beams

2.2. The Ranging Methodology Based on Multi-beam Troposcatter Group Delay

Figure 2 shows the side view of a multi-beam signal troposcatter model when the receiver and target are in azimuth alignment, where the receiver belongs to the passive ranging system station and the assumed BLOS target is a ship-borne frequency-scanned radar as introduced above in Section 2.1.

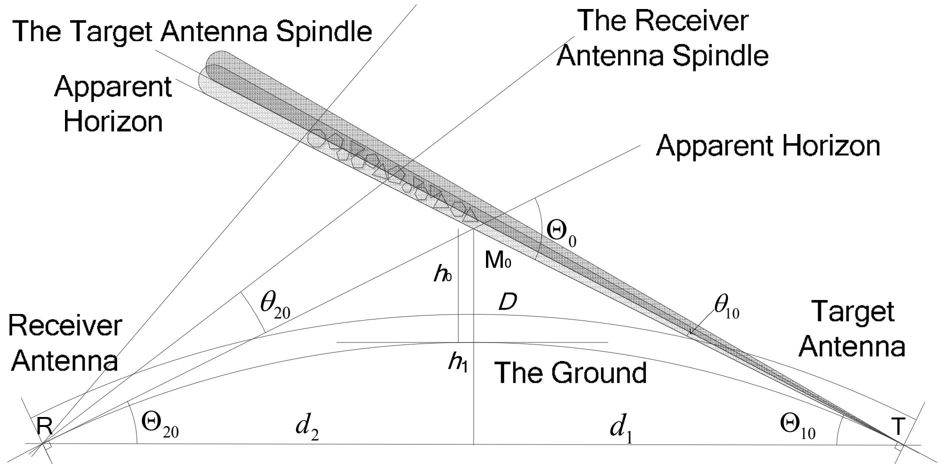


Fig. 2. *The side view of the troposcatter model of multi beam signal in vertical space*

In Fig. 2, the passive ranging system is represented by R, the assumed BLOS target is represented by T, Θ_0 is the minimum scattering angle (the angle between the scattered and incident directions at the lowest scatter point), M_0 is the lowest scatter point, Θ_{10}, Θ_{20} are the target and receiver antenna horizon angles, respectively, D is the earth surface distance between T and R, h_0 is the distance between M_0 and the ground, h_1 is the distance from M_0 to the connection line of T and R, θ_{10}, θ_{20} are the main elevation angle of target and receiver antenna, d_1, d_2 are the distances from the foot point of M_0 on the connection line of T and R to T, R. As shown in Fig. 2, frequency-scanned radar radiates multi-beam EM signals with different elevation angles in vertical space during a pulse period. When the EM signals are scattered in the troposphere, there are many paths from the target to the receiver in the generally large scatter common volume. As shown in Fig. 2 the area can be filled with irregular geometric objects; thus, the received signal is a superposing result of multipath propagation and its power is diffused in a period of delay time, which is usually called the power delay spectrum. Since the paths of different sub-beams to the receiving ends are diverse, there exist differences in the power delay spectrum belonging to different sub-beams.

2.2.1 Power Delay Spectrum Difference Between Sub-Beams: When a single-frequency signal is emitted through the propagation channel, the change is simply attenuated amplitude and shifted phase. Therefore, it is reasonable to model the troposcatter signal with a function that descripts the amplitude attenuation and phase shift information of the original emitted signal $x(f)$ as (1) in frequency domain

$$y(t,\mathbf{r})=\int E(t,f,\mathbf{r})x(f)\exp\left\{\mathrm{j}\left[2\pi ft+\varphi(t,f,\mathbf{r})\right]\right\}\mathrm{d}f \tag{1}$$

Where $y(t,\mathbf{r})$ denotes the received signal, $t, f, \mathbf{r}$ denote the time, frequency and spatial location, respectively, $E(t,f,\mathbf{r})$ represents the attenuated amplitude with the variation of $t, f, \mathbf{r}$ and $\varphi(t,f,\mathbf{r})$ represents the shifted phase. The transmission effect can be defined as:

$$H_{\text{tro}}(t,f,\mathbf{r}) = E(t,f,\mathbf{r})\exp\{\mathrm{j}\varphi(t,f,\mathbf{r})\} \tag{2}$$

This factor is called the transfer function. As shown in Fig 2, in the troposcatter channel the transfer function can be regarded as a generally stationary process in the time domain. Due to the multipath effect, the power delay spectrum emerges at the receiving end of R and has been simulated by a ray-tracing method recently in [10]. On the other hand, the power delay spectrum properties can also be obtained from the transfer function from the channel modelling perspective. Firstly, the correlation of the transfer function in frequency domain can be derived from (2) as:

$$R_H(\Delta f) = \overline{H^*_{\text{tro}}(t,f,\mathbf{r})H_{\text{tro}}(t,f+\Delta f,\mathbf{r})} \tag{3}$$

where $R_H(\Delta f)$ is the frequency correlation of the troposcatter transfer function along with the frequency separation Δf . Then, the power delay spectrum can be derived from the inverse Fourier transform of (3) as:

$$W(\tau) = \int R_H(\Delta f)\exp\{j2\pi\tau\Delta f\}\mathrm{d}(\Delta f) \tag{4}$$

where $W(\tau)$ is the power delay spectrum and τ is the delay length compared to the shortest propagation link. After dividing by the maximum value $W_{\max}$ of the spectrum, the normalized power delay spectrum $\omega(\tau)$ of a single beam propagation channel can be written as Equation (5.133) in [6] as

$$\omega(\tau) = \frac{W(\tau)}{W_{\max}} = \frac{Z}{Z_{\max}}\exp\left\{-b\left(Z^2+Z^2_{\max}\right)-m_1 Z+1\right\} \tag{5}$$

where $Z = \frac{\mathrm{c}\tau}{\Theta_0}$, c is the speed of light, $Z_{\max} = \frac{\sqrt{m_1^2+8b}-m_1}{4b}$ is the maximum power spectrum value along with the entire time delay of the received signal, $m_1 \approx \frac{1}{h_1}\left[m+\gamma h_1 - 2\left(\frac{\Theta_{20}\theta_{10}+\Theta_{10}\theta_{20}}{\psi'^{2}_{\text{ve}}}\right)\right]$, m is a parameter related to the weather conditions and media structure and is generally assumes a value of 5 in a Sea climate zone as in Table 2 of [4], γ is the refractive index of non-uniform distribution with height, for a maritime temperate ocean surface $\gamma = 0.27\mathrm{km}^{-1}$ as in Table. 2 of [4], $\psi_{\mathrm{ve}}'^{2} = \frac{\left(s_1\psi_{\mathrm{v1}}^2 + s_2\psi_{\mathrm{v2}}^2\right)}{8\ln 2}$, $s_1 = \frac{d_1}{d_2}$, $s_2 = \frac{d_2}{d_1}$, ψ_{v1}, ψ_{v2} are the vertical beam width of target and receiver antennas, $b = \frac{2\Theta_{10}\Theta_{20}}{h_1^2\psi_{\mathrm{ve}}'^{2}}$, respectively.

Differentiate $\omega(\tau)$ with delay τ, the maximum value of $\omega(\tau)$ is given as:

$$\tau_{\max} = \frac{Z_{\max}\Theta_0}{\mathrm{c}} \tag{6}$$

In order to describe the width of the power delay spectrum of the sub-beams, $T_{3\mathrm{dB}\alpha}$ is defined as the 3dB time width of the delay spectrum of the sub-beams when the target antenna elevation angle is α, and $\tau_{3\mathrm{dB}\alpha}^{1}$, $\tau_{3\mathrm{dB}\alpha}^{2}$ ($\tau_{3\mathrm{dB}\alpha}^{1} < \tau_{3\mathrm{dB}\alpha}^{2}$) is the time when the power reduces to $Z_{\max}/2$ in the delay spectrum. Thus, $\tau_{3\mathrm{dB}\alpha}^{1}$, $\tau_{3\mathrm{dB}\alpha}^{2}$ are the two solutions of the equation $2Z\exp\left\{-b\left(Z^2 + Z_{\max}^2\right) - m_1 Z + 1\right\} = Z_{\max}$. After the equation is solved, the 3 dB time width can be obtained as

$$T_{3\mathrm{dB}\alpha} = \tau_{3\mathrm{dB}\alpha}^{2} - \tau_{3\mathrm{dB}\alpha}^{1} \tag{7}$$

In order to describe the relationship of the power delay spectrum of the sub-beams, $\Delta\tau_{\mathrm{m}\alpha\beta}$ is defined as the time difference of the maximum power of the sub-beam delay spectrum when the target antenna elevation angle is α and β ($\alpha < \beta$), namely, group delay

$$\Delta\tau_{\mathrm{m}\alpha\beta} = \frac{\Theta_0\left[Z_{\max}(\beta) - Z_{\max}(\alpha)\right]}{\mathrm{c}} \tag{8}$$

where $Z_{\max}(\alpha)$, $Z_{\max}(\beta)$ are the maximum power of sub beam α, β delay spectrum when the elevation angle are α, β, respectively.

Now that the group delay and the 3dB time width are given, the correspondence with the target distance is to be studied. Figure 3 shows the relationship of the sub-beam power delay spectrum and the target distance according to (5) when the antenna azimuth is aligned, target and receiving antennas are erected at sea level, the receiving antenna vertical beam width ψ_{v2} is 0.5°, the elevation angle is 0.5°, the transmitting antenna vertical beam width ψ_{v1} is 1.5°, and the elevation angles are 0° and 1° ($\alpha=0^{\circ}$, $\beta=1^{\circ}$).

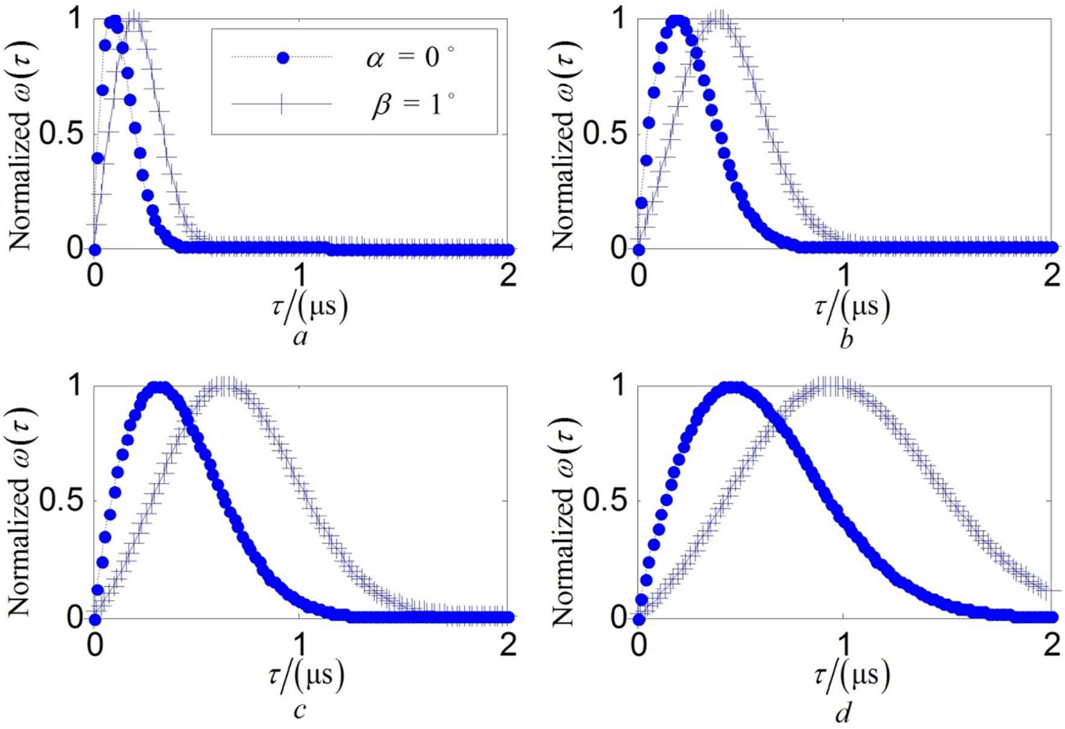


Fig. 3. The relationship of two beam signal delay spectrums

a The power delay spectrum $\omega(\tau)$ of two beam signals, when target distance D=300km

b The power delay spectrum $\omega(\tau)$ of two beam signals, when target distance D=400km

c The power delay spectrum $\omega(\tau)$ of two beam signals, when target distance D=500km

d The power delay spectrum $\omega(\tau)$ of two beam signals, when target distance D=600km

Therefore, once the receiving antenna parameters are set up, the 3dB time width $T_{3\mathrm{dB}\alpha}$ of the single beam and the group delay $\Delta\tau_{\mathrm{m}\alpha\beta}$ of sub-beams both have a monotonically increasing relationship with target distance D, thus the bigger D is, the bigger $T_{3\mathrm{dB}\alpha}$ and $\Delta\tau_{\mathrm{m}\alpha\beta}$ are. Moreover, there is definitely a one-to-one correspondence between $\Delta\tau_{\mathrm{m}\alpha\beta}$ and D. Given that the received signal group delay can be estimated after the detection of the troposcatter signal, the target distance to the receiver station can be obtained by the estimated group delay of the received multibeams and its mathematical relationship to the target distance as derived in (5) to (8), namely, single station passive ranging based on group delay.

To evaluate the ranging performance, two evaluating indicators are proposed as ranging resolution and delay-measure requirements. Supposing that $\Delta\tau_{\mathrm{m}\alpha\beta}(D)$ is the sub-beam group delay when the target antenna elevation angles are α, β, and the earth surface distance between target and receiver antenna is

D as is shown in Figure 2. Then the relationship of group delay and target distance can be utilized to describe the ranging performance i.e. the ranging resolution as:

$$d\tau_{\alpha\beta} = \frac{\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_1\right) - \Delta\tau_{\mathrm{m}\alpha\beta}\left(D_2\right)}{D_1 - D_2} \tag{9}$$

where D_1, D_2 denote two target distances in the potential detection range, $d\tau_{\alpha\beta}$ is the resolution ratio of the proposed passive ranging, which enlarges with the increasing interval between group delay of sub-beams α and β for the same receiver and processing system. In addition, the delay-measure requirement $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$ is defined as the system time delay measurement requirement of the adjacent sub-beam group delay under minimum D (i.e. minimum $\Delta\tau_{\mathrm{m}\alpha\beta}$) within the potential detection range, when the transmitting antenna elevation angles are α and β, respectively.

2.2.2 Signal Power Difference Between Sub-Beams: The proposed ranging mechanism is validated through the propagation loss and the received signal power point of view in this section. In Zhang's Troposcatter model, the beam width and elevation angle of the target antenna will affect the median value of the received signal power, for which the general form [6] is:

$$P_{\mathrm{r}} = P_{\mathrm{t}} G_{\mathrm{tm}} G_{\mathrm{rm}} AUVW \tag{10}$$

where P_{r} is the medium value of the receiving signal power, P_{t} is the target emitting signal power, G_{tm}, G_{rm} are the target and receiver antenna gain, respectively, A is a factor related to path loss and atmospheric absorption, U represents the contribution of the target and receiver antenna parameters on azimuth direction, V denotes the influence of the receiver antenna parameters on vertical direction as elevation angle, vertical beam width and the erection height, W denotes the influence of the target antenna parameters on vertical direction as elevation angle, vertical beam width and the erection height.

Since most of the potential targets under passive ranging applications are uncooperative, it's essential to investigate the limitations of the proposed ranging mechanism to the uncooperative target. For a multi-beam emitting situation, we define β_{Tv} to describe the received signal power factor determined by the target antenna parameter of elevation angle, beam width and erection height, which constitutes a part of the received power median value as:

$$\beta_{\mathrm{Tv}} = W = \int_0^\infty \exp\left\{-b_1\left(\theta_1 - \theta_{10}\right)^2 - 2c_1\theta_1\right\}\left[1 - \cos\left(2kh_{\mathrm{te}}\theta_1\right)\right]d\theta_1 \tag{11}$$

where $k=\frac{2\pi}{\lambda}$, $b_1=\frac{4\ln 2}{\psi_{\mathrm{v}1}^2}$, $b_2=\frac{4\ln 2}{\psi_{\mathrm{v}2}^2}$, $c_1=\frac{m+\gamma h_1}{2\Theta_0}s_1$, $c_2=\frac{m+\gamma h_1}{2\Theta_0}s_2$, λ is the signal wave length, h_{te} is the effective height of the target antenna.

When the target emits a signal at S band, the ship borne target antenna is at sea level, the elevation angle of the receiving antenna is optimized to the target, and antenna azimuth is in mutual alignment, then the median value of the received signal power can be attributed only to β_{Tv}, which is related to the distance D, the target elevation angle θ_{10} and its beam width $\psi_{\mathrm{v}1}$. Fig. 4 shows the variation tendency of a normalized multi-beam received power factor β_{Tv} along with θ_{10}, $\psi_{\mathrm{v}1}$ for different target distances D according to (11).

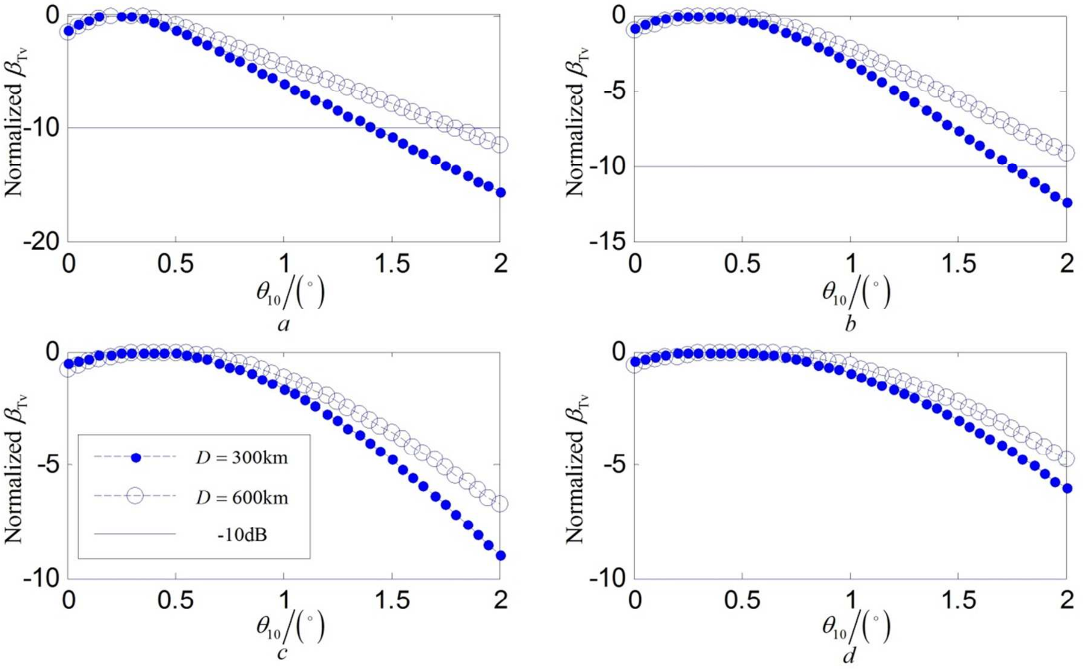


Fig. 4. *The relationship of normalized β_{Tv} and θ_{10}, $\psi_{\mathrm{v}1}$ for different D*

a The relationship of normalized power factor β_{Tv} and transmitting elevation angle θ_{10} for different target distance D, when transmitting vertical beam width $\psi_{\mathrm{v}1}=0.5^\circ$

b The relationship of normalized β_{Tv} and θ_{10} for different D, when $\psi_{\mathrm{v}1}=1.0^\circ$

c The relationship of normalized β_{Tv} and θ_{10} for different D, when $\psi_{\mathrm{v}1}=1.5^\circ$

d The relationship of normalized β_{Tv} and θ_{10} for different D, when $\psi_{\mathrm{v}1}=2.0^\circ$

As is shown in Fig. 4, when the target antenna elevation angle varies within 1.5°, the normalized multi beam power factor β_{Tv} fluctuates within 10dB; when the elevation angle beam width of the target antenna is greater than or equal to 1°, together with the elevation angle changes within 1°, the normalized multi-beam power factor β_{Tv} fluctuates within 3dB.

Therefore, in the working period of the target frequency-scanned radar, the troposcatter target emitting signal can be used for the group delay calculation as long as the target beam elevation angle is less than 1.5°, which is in accordance with most ship borne occasions, then the BLOS troposcatter passive ranging is able to be conducted in a single station. Thus, the most critical issue to improving the ranging performance is the parameter selection problem regarding receiving antenna elevation angle θ_{20}, vertical beam width ψ_{v2}, erection height h_{re}, etc., which are the indispensable constituents of the receiving antenna model.

3. Analysis of the Receiving Mode of Single Station Passive Ranging Antenna

As to the troposcatter passive detection system, the array form is often taken as receiving antenna mode in the horizontal direction to cover a wide spatial range and estimation of the target direction, while the vertical direction of the receiving antenna is mainly used for signal energy accumulation. Equation (5) shows that the receiving antenna elevation parameters have a direct effect on the power delay spectrum of received signals. The receiving antenna elevation parameters include elevation angle and its beam width; in addition, the receiving antenna erection height affects the delay spectrum profoundly as well. Therefore, to implement the target positioning of BLOS frequency-scanned radar by utilizing the group delay properties of troposcatter signals, the three parameters of the receiving antenna mode mentioned above need to be researched in detail.

3.1. Analysis of Elevation Angle of Receiving Antenna

As to Zhang's Troposcatter model, both the beam width ψ_{v2} and elevation angle θ_{20} of the receiving antenna have an impact on the medium value of the received signal power, just as factor V in equation (10), meanwhile the antenna gain changes with the fluctuation of the beam width ψ_{v2}. Thus, we define β_{Rv} as the factor of troposcatter receiving antenna elevation power as

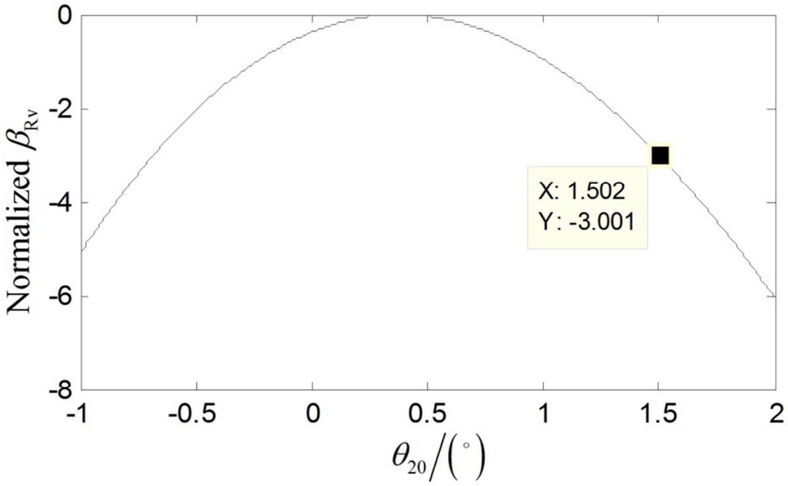
$$\begin{aligned}\beta_{\mathrm{Rv}} &= G_{\mathrm{rm}}V \\ &= G_{\mathrm{rm}}\int_0^{\infty}\exp\left\{-b_2\left(\theta-\theta_{20}\right)^2-2c_2\theta\right\}\cdot\left[1-\cos\left(2kh_{\mathrm{re}}\theta\right)\right]d\theta\end{aligned} \tag{12}$$

where G_{rm} is the receiving antenna main lobe gain, h_{re} is the effective height of the receiving antenna, the other parameters are the same as (5). According to antenna theory, for a certain frequency band, the narrower the antenna beam is, the higher the antenna gain is, and the established equation of the relationship between antenna gain and beam width can be denoted as in [16]

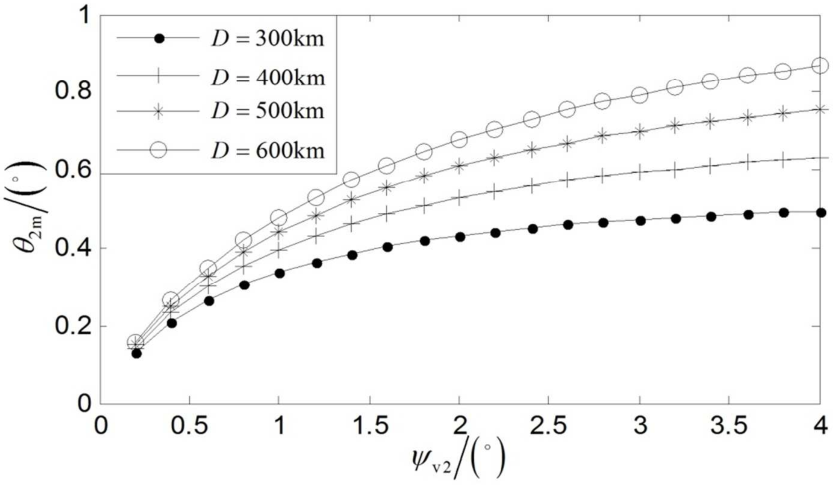
$$G(\mathrm{dBi}) = 10\lg\frac{K}{\psi_{\mathrm{h}}\psi_{\mathrm{v}}} \tag{13}$$

where $\psi_{\mathrm{h}} = k_{\mathrm{h}}\frac{\lambda}{L_{\mathrm{h}}}$, $\psi_{\mathrm{v}} = k_{\mathrm{v}}\frac{\lambda}{L_{\mathrm{v}}}$, λ is the wavelength, K is a constant related to the antenna shape, ψ_{h}, ψ_{v} are the 3dB beam width in azimuth and vertical direction, respectively. L_{h}, L_{v} are the length of antenna aperture in azimuth and vertical direction, respectively and k_{h}, k_{v} are the efficiency factors of the angle dimension.

3.1.1 Analysis of Receiving Antenna Elevation Angle When the Ranging Distance is Fixed: When the receiving antenna azimuth is in alignment, target signal frequency, distance and the receiving antenna erection height are fixed, an optimum elevation angle of the receiving antenna can be derived by equation (12) to maximize the received signal power. Suppose the receiving antenna is at sea level, the receiving antenna vertical beam width ψ_{v2} and the earth surface distance D are given, then the relationship between β_{Rv} and the receiving antenna elevation angle θ_{20} can be derived by (12) as shown in Fig. 5.



a



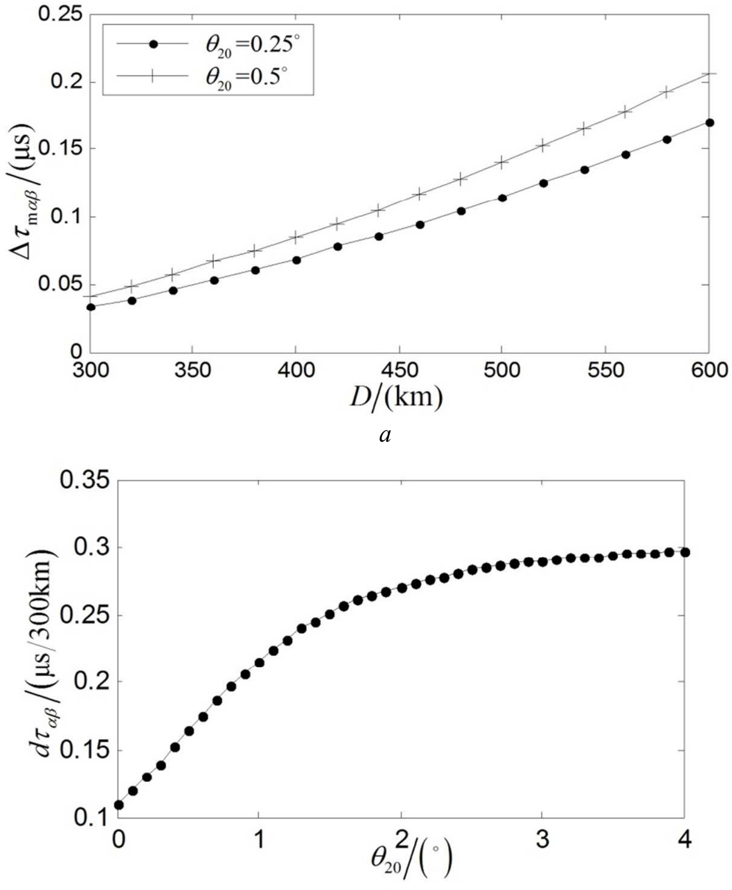
b

Fig. 5. *The influence on receiving signal power of the change of receiving pattern*
a The relationship of normalized receiving antenna elevation power factor β_{Rv} and elevation angle θ_{20}
b The relationship of optimal receiving antenna elevation angle $\theta_{2\text{m}}$ and the receiving antenna vertical beam width $\psi_{\text{v}2}$ for different target distance

As shown in Figure 5(a), if the receiving antenna beam is too high or too low, the mid-range value of received signal power will decrease, so there is an optimum receiving elevation that maximizes the median value of received power. From equation (10) and equation (12), we learn that the optimal elevation angle $\theta_{2\text{m}}$ is determined by the receiving antenna vertical beam width $\psi_{\text{v}2}$ and the target distance D, but not the target transmitting antenna elevation angle or its beam width, so it is reasonable for the passive ranging system to accommodate different target antennas in certain distances through the optimal receiving antenna elevation angle and maximize the received signal power. As is shown in Figure 5(b), after analysing the optimal elevation angle in different conditions, we can reach the conclusion that the receiving antenna optimal elevation angle increases with the increasing target distance and the elevation angle beam width.

3.1.2 Analysis of the Receiving Antenna Elevation Angle when the Ranging Distance Range is Fixed: The actual system is always expected to detect a potential target's presence within some distance range other than a fixed distance; therefore, we will discuss how to select the optimal elevation angle of a receiving antenna under these circumstances. The results in Fig. 5(b) show that the variation range of the optimal receiving antenna elevation angle is small, within 300km to 600km, thus the receiving antenna may fix the elevation angle in the vertical direction without scanning to simplify the system, while the fixed elevation should take all the potential targets within the detection range into consideration.

According to [4], the troposcatter propagation loss increases with increasing distance D. For the sake of enhancing the received signal power, the receiving antenna elevation angle should be the same as the optimal elevation angle corresponding to the furthest distance in the fixed distance range. When the receiving antenna elevation angle is the same as the optimal elevation angle corresponding to the furthest distance, the propagation loss of the furthest target is still larger than the proximal one according to [4]. However, the loss difference between them decreases due to the receiving antenna corresponding to the furthest target, which is conducive to the target detection performance. The performance is investigated with its evaluating indicators in Fig. 6.



b

Fig. 6. *The influence of θ_{20} on ranging*

a The relationship of group delay $\Delta\tau_{m\alpha\beta}$ and target distance D for different receiving elevation angle

b The relationship of ranging resolution $d\tau_{\alpha\beta}$ and receiving elevation angle θ_{20}

Figure 6(a) shows the relationship of the group delay $\Delta\tau_{m\alpha\beta}$ ($\alpha=0^\circ, \beta=0.5^\circ$) and the target distance for different receiving antenna elevation angles, 0.25° and 0.5°, when the target antenna vertical beam width is 1.5° and the receiving antenna vertical beam width is 0.5°. Given the two elevation angles, equation (12) shows that the optimal elevation angle for the receiving antenna to maximize the received signal power is 0.25°, while the ranging resolution of the group delay $d\tau_{\alpha\beta}$ is better at 0.5° according to

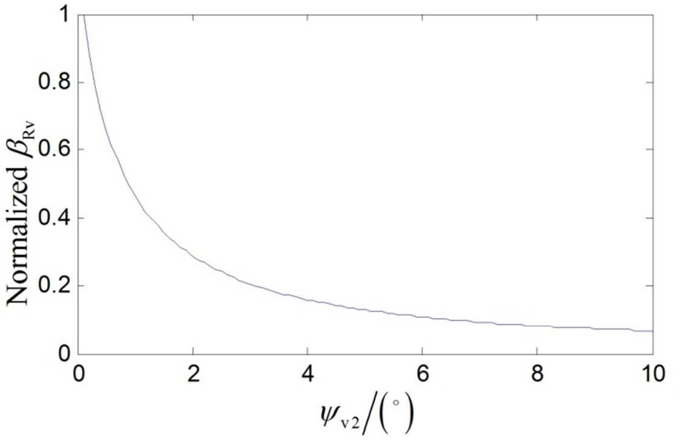
(9), and the delay-measure requirement $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$ decreases as well. Furthermore, Fig. 6(b) shows the relationship between ranging resolution and receiving antenna elevation angle in the same conditions as Fig. 6(a). The ranging resolution increases with increasing receiving antenna elevation angle and finally tends to a stable best value.

The actual receiving antenna elevation angle should take both the received signal power and the ranging performance into consideration together to design the ideal elevation angle for a practical system.

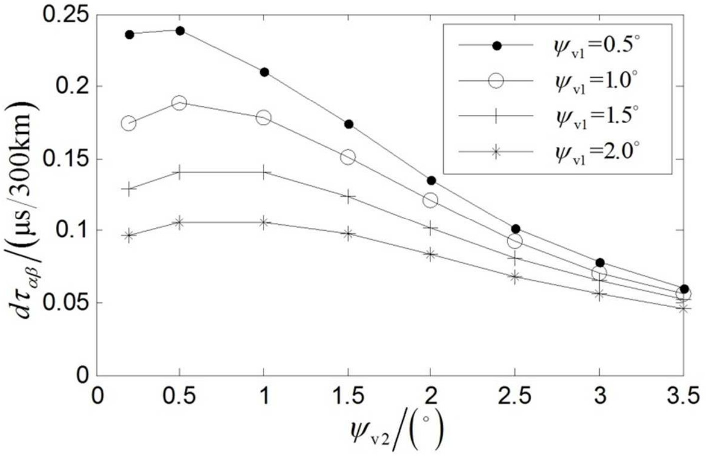
3.2. Analysis of Receiving Antenna Vertical Beam Width

The receiving antenna vertical beam width depends mainly on the antenna vertical size once the working frequency band is fixed, and a bigger size brings a smaller beam width, a greater gain, and the power delay spectrum varies accordingly.

3.2.1 Analysis of the Received Signal Power under the Influence of Receiving Antenna Vertical Beam Width: Fig. 7(a) shows the relationship of the normalized power factor of a receiving antenna β_{Rv} and a receiving antenna vertical beam width ψ_{v2} according to (12) when the receiving antenna has optimal elevation angle as is given in Section 3.1.



a



b

Fig. 7. *The influence on the received signal power factor and the ranging performance with different receiving antenna vertical beam widths*

a The relationship between normalized receiving antenna elevation power factor β_{Rv} and vertical beam width ψ_{v2} at the optimal elevation angle

b The deviation of group delay resolution $d\tau_{\alpha\beta}$ along with the transmitting antenna vertical beam width ψ_{v1} and receiving antenna vertical beam width ψ_{v2}, when receiving antenna height is $h_{re}=0$

As shown above, the receiving power factor at the optimal elevation angle increases steadily with decreasing beam width. Thus, from the receiving signal power point of view, the greater vertical size of the receiving antenna, the better. However, as to the troposcatter passive ranging system, the receiving antenna vertical size influences not only the received signal power, but also the group delay $\Delta\tau_{m\alpha\beta}$ of different sub-beams, the passive ranging resolution $d\tau_{\alpha\beta}$ and the delay-measure requirement $\Delta\tau_{m\alpha\beta}$.

3.2.2 Analysis of the Power Delay Spectrum under the Influence of Receiving Antenna Vertical Beam Width: Fig. 7(b) shows the two beam path ($\alpha=0^\circ$, $\beta=0.5^\circ$) group delay resolution $d\tau_{\alpha\beta}$ (as in (9)) variation along with the receiving antenna vertical beam width ψ_{v2} in different conditions of target antenna vertical beam width ψ_{v1} when the receiving antenna is erected at sea level, the detection range is 300-600km and the receiving antenna elevation angle is fixed to the optimal angle of 600km. This is the situation that was analysed in Section 3.1.2 above.

As shown in Fig. 7(b), the ranging resolution $d\tau_{\alpha\beta}$ increases with decreasing beam width; the resolution is higher when the receiving antenna vertical beam width is less than 1°; mid-range when the beam width is between 1° and 2°; lower when the beam width is more than 2°. However, it should be noted that the increase of the ranging resolution is not strictly uniform. For instance, in calculating the conditions of Fig. 7(b), the ranging resolution at beam width 0.5° is higher than the resolution at beam width 0.2°.

As to the delay-measure requirement $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$ and 3dB time width $T_{3\mathrm{dB}\alpha}$ related to different receiving antenna vertical beam widths, four calculated results are given according to (8) assuming that the receiving antenna is erected at sea level, the target antenna vertical beam width is 1.5°, α=0°, β=0.5°, the distance is 300km, the receiving antenna elevation angle is the same as the optimal elevation angle at 600km.

When the receiving antenna vertical beam width $\psi_{\mathrm{v}2}$ is 0.2°, $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$=0.033μs , $T_{3\mathrm{dB}\alpha}$=0.148μs ;

When the receiving antenna vertical beam width $\psi_{\mathrm{v}2}$ is 0.5°, $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$=0.036μs , $T_{3\mathrm{dB}\alpha}$=0.162μs ;

When the receiving antenna vertical beam width $\psi_{\mathrm{v}2}$ is 1.0°, $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$=0.034μs , $T_{3\mathrm{dB}\alpha}$=0.183μs ;

When the receiving antenna vertical beam width $\psi_{\mathrm{v}2}$ is 2.0°, $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$=0.021μs , $T_{3\mathrm{dB}\alpha}$=0.210μs .

It should be noted that for certain target vertical beam widths, the delay-measure requirement $\Delta\tau_{\mathrm{m}\alpha\beta}\left(D_{\min}\right)$ does not strictly decrease with decreasing beam width $\psi_{\mathrm{v}2}$; however, the narrower the receiving antenna vertical beam width $\psi_{\mathrm{v}2}$ is, the smaller the beam path channel 3dB time width $T_{3\mathrm{dB}\alpha}$ is, and thus the signal time diffusion is reduced.

3.3. Analysis of Receiving Antenna Erection Height

Receiving antenna height affects not only the received signal power, but also the ranging resolution and the delay-measure requirement.

3.3.1 The Effect on Main Loss by Receiving Antenna Erection Height: According to Zhang's model of the prediction on troposcatter propagation loss, the main basic propagation loss [6] can be represented as:

$$L_{b0} = F + 30\lg f + 30\lg\Theta_0 + 10\lg d + 20\lg\left(5+\gamma h_1\right) + 4.343\gamma h_0 \tag{14}$$

where F is the meteorological factor (dB), and can be valued as $\mathrm{F}=26\mathrm{dB}$ on the maritime temperate sea surface according to [6], f is frequency (kHz), d is the path length (km) which can be calculated by the channel geometry as in Fig. 2, h_0, h_1 are shown in Fig. 2, the remaining parameters are the same as (5).

The calculation results of (14) show that the greater the receiving antenna erection height, the lower the main basic propagation loss. For example, the main basic propagation loss can be reduced about 5dB by increasing the antenna height from the sea level to 1000m when the distance, D between target, T and receiver, R is 300km, and the loss reduction continues to decrease with increasing distance. For the above example, the main basic propagation loss reduction decreases to about 3dB when the distance between the transmitting and receiving antennas is 600km. In terms of the received signal power, increasing the receiving antenna height will have the greatest effect, if the above conditions are satisfied.

3.3.2 The Effect on Power Delay Spectrum by Receiving Antenna Erection Height: Fig. 8 shows the relationship between the receiving antenna vertical beam width ψ_{v2} and the two beam path channel group delay resolution $d\tau_{\alpha\beta}$ (as in (9)) under the same conditions as Fig. 7(b) except that the receiving antenna erection height is 1000m.

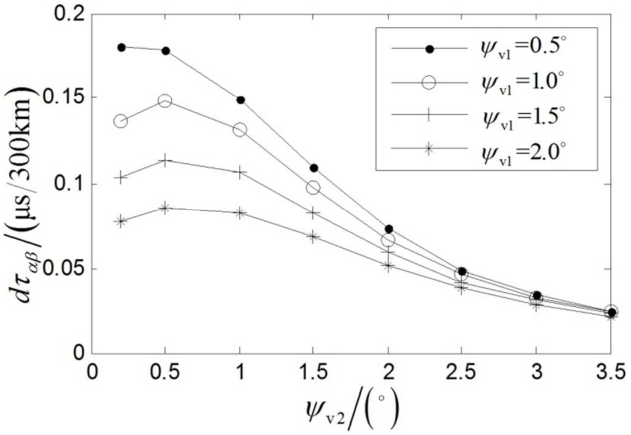


Fig. 8. *The deviation of group delay resolution* $d\tau_{\alpha\beta}$ *along with the transmitting and receiving antenna vertical beam widths* ψ_{v1} ψ_{v2}*, respectively when receiving antenna height is* $h_{\mathrm{re}}=1000\mathrm{m}$

Compared with Fig. 7(b), it is seen that given the same conditions, the higher the receiving antenna erection height, the lower the ranging resolution. As to the delay-measure requirement $\Delta\tau_{\mathrm{m}\alpha\beta}(D_{\min})$ and 3dB time width $T_{3\mathrm{dB}\alpha}$ related to different receiving antenna vertical beam widths, four calculated results are given according to (8) given that the receiving antenna erection height is 1000m, the transmitting antenna vertical beam width is 1.5°, $\alpha=0^\circ$, $\beta=0.5^\circ$, the distance is 300km, and the receiving antenna elevation angle is the same as the optimal elevation angle at 600km.

When the receiving antenna vertical beam width ψ_{v2} is 0.2°, $\Delta\tau_{\mathrm{m}\alpha\beta}(D_{\min})=0.013\mu\mathrm{s}$, $T_{3\mathrm{dB}\alpha}=0.061\mu\mathrm{s}$;

When the receiving antenna vertical beam width ψ_{v2} is 0.5°, $\Delta\tau_{\mathrm{m}\alpha\beta}(D_{\min})=0.013\mu\mathrm{s}$, $T_{3\mathrm{dB}\alpha}=0.071\mu\mathrm{s}$;

When the receiving antenna vertical beam width ψ_{v2} is 1.0°, $\Delta\tau_{\mathrm{m}\alpha\beta}(D_{\min})=0.008\mu\mathrm{s}$, $T_{3\mathrm{dB}\alpha}=0.080\mu\mathrm{s}$;

When the receiving antenna vertical beam width ψ_{v2} is 2.0°, $\Delta\tau_{\mathrm{m}\alpha\beta}(D_{\min})=0.002\mu\mathrm{s}$, $T_{3\mathrm{dB}\alpha}=0.083\mu\mathrm{s}$.

Compared with the results in Section 3.2.2, the delay-measure requirement $\Delta\tau_{m\alpha\beta}\left(D_{\min}\right)$ grows with increasing receiving antenna erection height. However, the higher the receiving antenna erection is, the smaller the beam path channel 3dB time width is, and thus the signal time diffusion is reduced.

4. **Consideration of Fading influence**

Troposcatter propagation, by virtue of its own nature, is subject to strong multipath, Rayleigh fading, diurnal and seasonal variations, etc. - received signals are highly variable even if the scenario is stable. These variations are exhibited on both phase and amplitude, since the proposed ranging mechanism focuses mainly on the received signal power. We consider then the influence of amplitude variation on the received signal, referred to as fading influence. According to the observed time length, fading can be divided to fast fading, which describes the instantaneous amplitude variation in minutes to hours, and slow fading, which counts the medium amplitude variation in days to years. Slow fading basically reflects the propagation reliability and can be generally descripted using Equation (6) in [4] as:

$$Y\left(q\right)=C\left(q\right)Y\left(90\right) \tag{15}$$

Where the conversion factor $Y\left(q\right)$ is the fading margin with non-exceedance percentages, q and can be estimated by the coefficient, $C\left(q\right)$ together with 90% conversion factor, $Y\left(90\right)$. According to Figure 2(d) of [4], the basic propagation loss difference between $q=90\%$ and the medium amplitude ($q=50\%$) is less than 1 dB for BLOS distance over 600 km under Sea climate zone. However, it does have an impact on the group delay based ranging due to the variation of the sub-beam maximum power $Z_{\max}\left(\alpha\right)$, $Z_{\max}\left(\beta\right)$ as in (8). The likely result is that an estimated group delay changes within a specific range, e.g. 0.047 μs (the calculated situation in Fig. 3(d) where the variation of $Z_{\max}\left(\alpha\right)-Z_{\max}\left(\beta\right)$ is 2 dB), and finally leads to a ranging ambiguity of about 50 km. In addition, fast fading describes the fluctuation of the received signal amplitude in the short-term; despite the first and second order statistic properties analysed profoundly in [6], we focus mainly on the fading duration, which is defined as (the total amount of time during which the amplitude is below the median value within in a given sample period, T_{sample})/(The total number of fluctuations of times in T_{sample}) as Equation (6.135) in [6]. According to the theoretical results, the fading duration is 0.02s~1.61s (according to Table 6.3 in [6]) for a target BLOS distance of 600 km with a frequency band of 2 GHz to 5 GHz. Moreover, the duration increases with the decreasing of distance and frequency.

In order to adapt the proposed ranging method to a more practical environment with multipath fading, diversity may be a valuable technique to deal with the fading fluctuations e.g. space diversity (multiantenna receiver), frequency diversity, angular diversity (multi-beam forming technique), etc. As to the fast fading, it's better for the receiver to adopt a real-time detector (estimator), since the pulse duration and the pulse period of a typical frequency-scanned radar is about several to hundreds of microseconds, which is much less than the fading duration. Then detectors generating a reliable result within tens of pulse samples are acceptable, which can therefore relieve the deterioration caused by propagation impairments to the ranging method based on group delay.

5. Conclusion

This paper takes frequency-scanned radar as a detection target, according to the troposcatter signal power median value and its delay spectrum of different sub-beams emitting from the target antenna in the vertical direction. A troposcatter passive ranging method is proposed based on the utilization of the one-to-one correspondence between the sub-beam group delay and the target distance. Then some indicators, such as the passive ranging resolution, 3dB time width of the delay spectrum, the delay-measure requirement, and the normalized power factors are defined to describe the passive ranging performance. Based on the evaluation of these indicators, the receiving antenna mode is analysed and the conclusions reached are: there is an optimal elevation angle of receiving antennas to maximize the received signal power, with the increase of the receiving antenna elevation angle, the ranging resolution of group delay increases, and the requirements of system time delay measurement are reduced; the received signal power increases with decreasing receiving antenna beam width, there is an optimal vertical beam width of the receiving antenna to maximize the ranging resolution; by increasing the receiving antenna erection height, the main propagation loss decreases, and the received signal power increases, while the time delay resolution declines, the requirements of system time delay measurement increase. These conclusions are significant to the receiving method design of single station passive ranging antennas based on troposcatter propagation. Finally, the performance deterioration under troposcatter multipath fading is considered with some advice to adopt diversity reception and real-time detectors.

6. References

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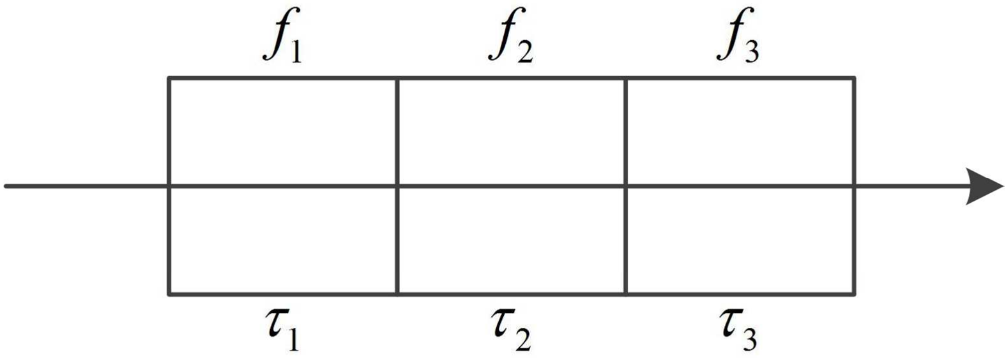
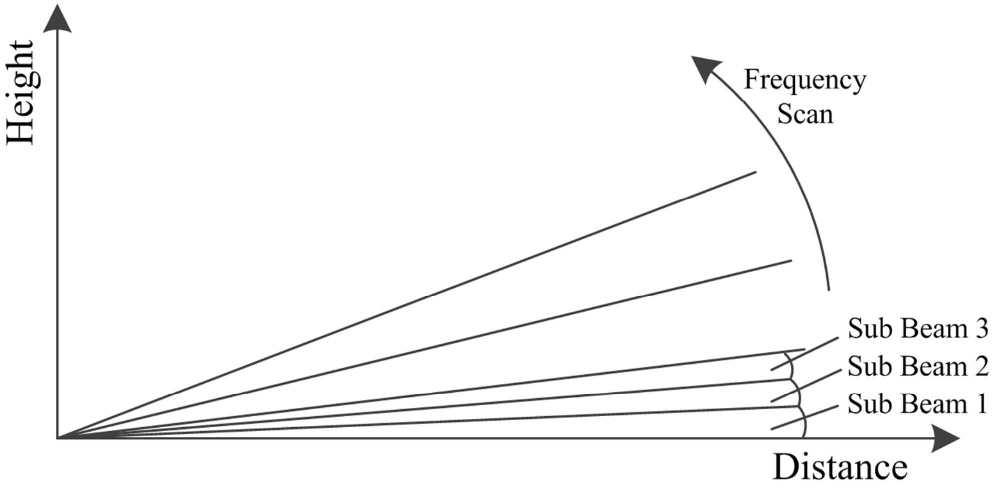


a The wave of transmitting pulse
120x45mm (300 x 300 DPI)



b The diagram of beam
108x53mm (300 x 300 DPI)

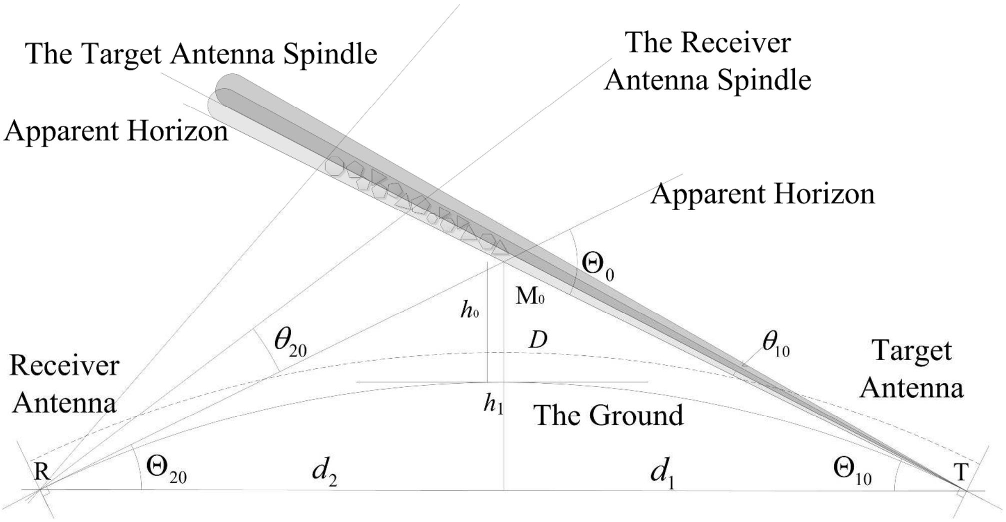
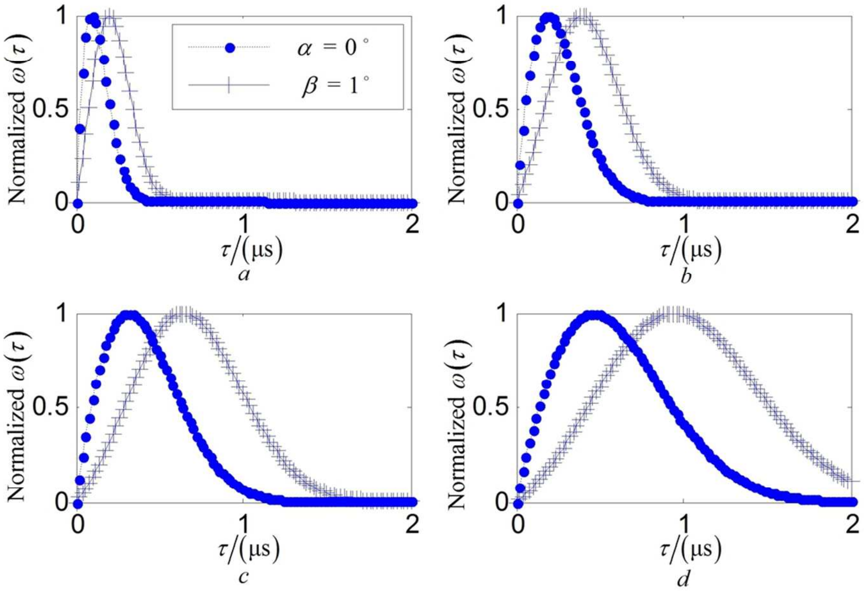
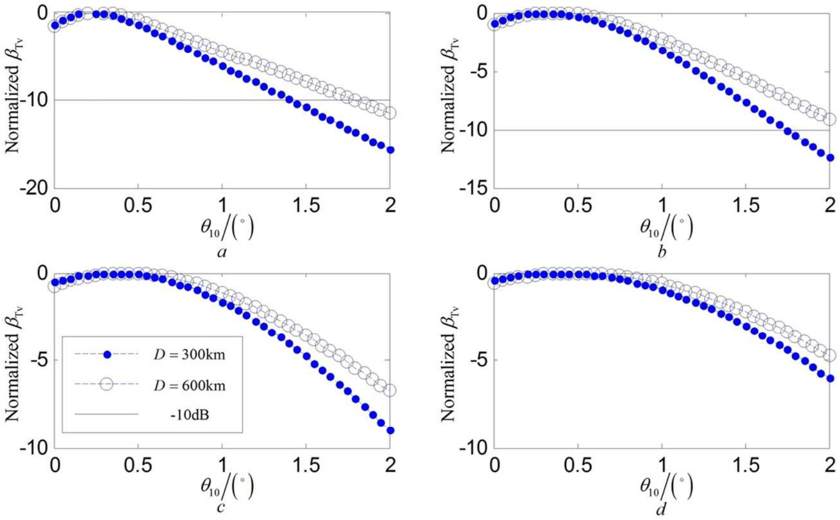


Fig. 2. The side view of the troposcatter model of multi beam signal in vertical space
1020x525mm (96 x 96 DPI)

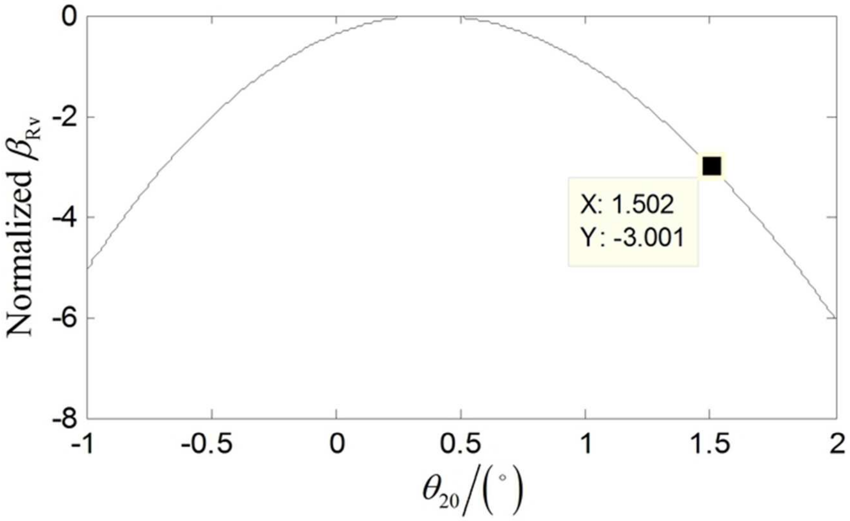


a The power delay spectrum of two beam signals, when target distance *D*=300 km
b The power delay spectrum of two beam signals, when target distance *D*=400 km
c The power delay spectrum of two beam signals, when target distance *D*=500 km
d The power delay spectrum of two beam signals, when target distance *D*=600 km

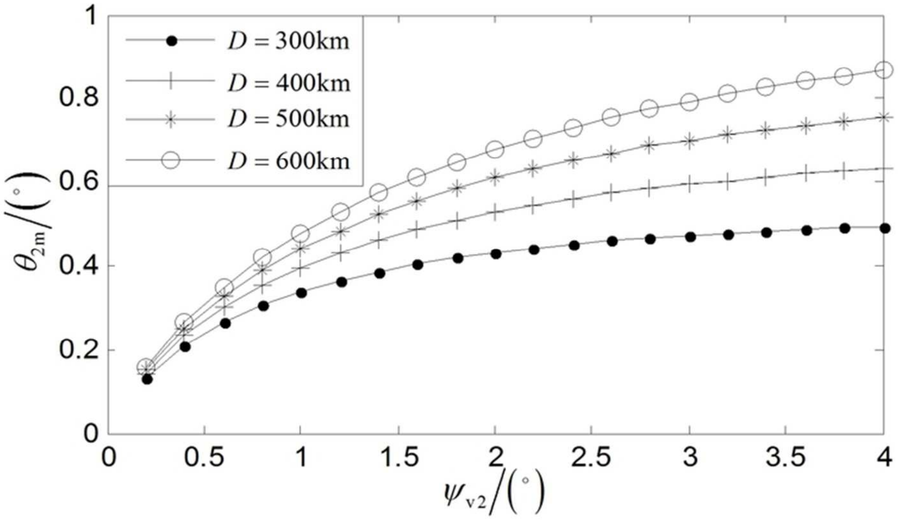
110x70mm (300 x 300 DPI)



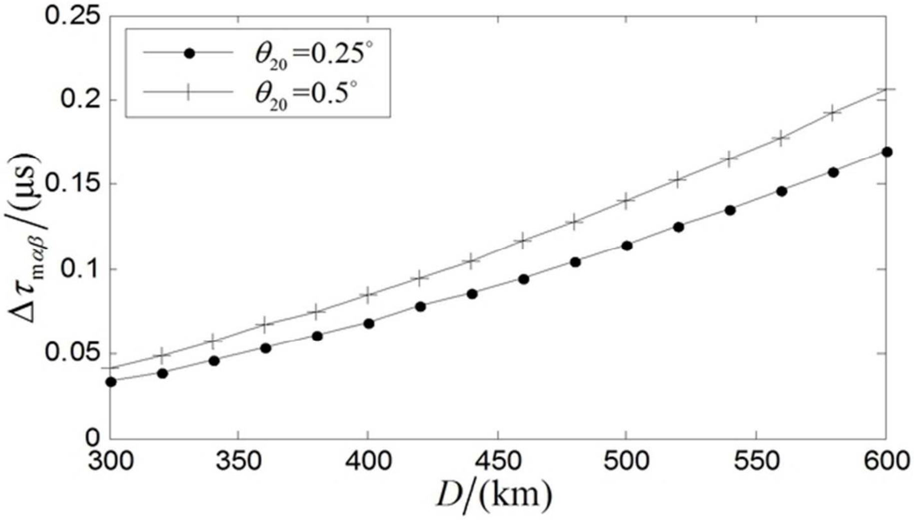
a The relationship of normalized power factor β_{Tv} and transmitting elevation angle θ_{10} in different target distance *D*,when transmitting vertical beam width ψ_{v1}=0.5°\r\nb The relationship of normalized β_{Tv} and θ_{10} in different *D*, when ψ_{v1}=1.0°\r\nc The relationship of normalized β_{Tv} and θ_{10} in different *D*, when ψ_{v1}=1.5°\r\nd The relationship of normalized β_{Tv} and θ_{10} in different *D*, when ψ_{v1}=2.0°
125x70mm (300 x 300 DPI)



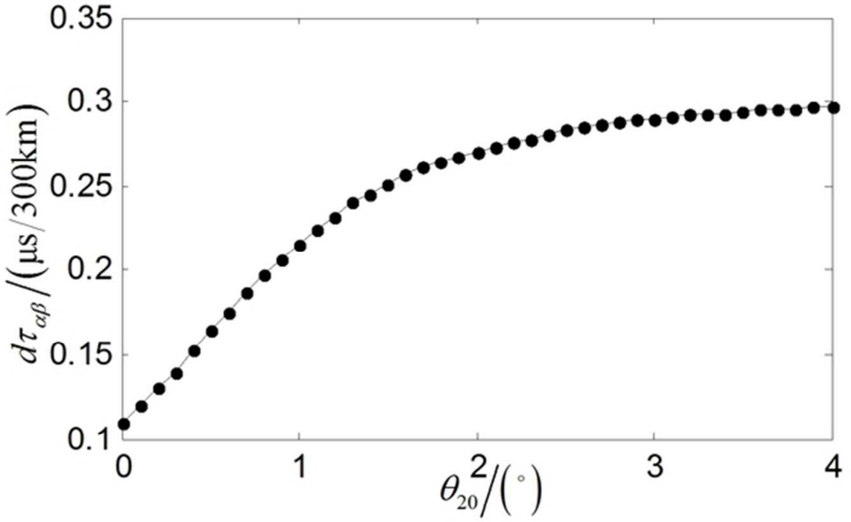
a The relationship of normalized receiving antenna elevation power factor β_{Rv} and elevation angle θ_{20}
71x38mm (300 x 300 DPI)



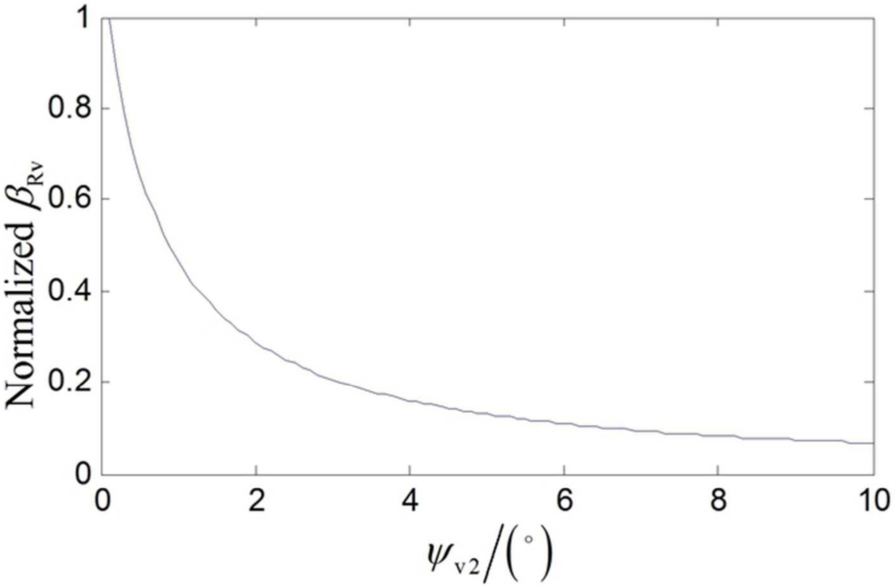
b The relationship of optimal receiving antenna elevation angle θ_{2m} and the receiving antenna vertical beam width ψ_{v2} in different target distance
71x38mm (300 x 300 DPI)



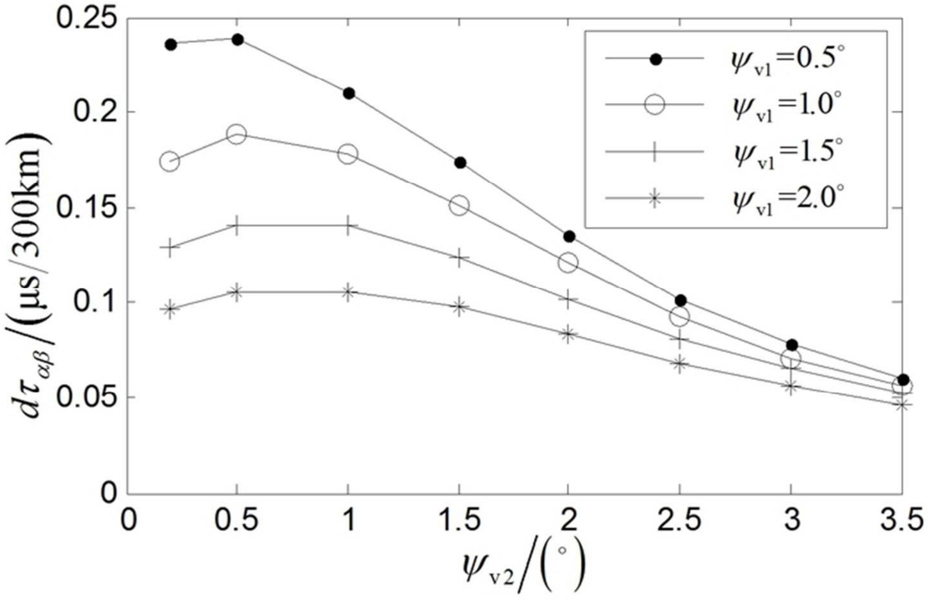
a The relationship of group delay and target distance *D* in different receiving elevation angle
61x33mm (300 x 300 DPI)



b The relationship of ranging resolution and receiving elevation angle θ_{20}
61x33mm (300 x 300 DPI)



a The relationship between normalized receiving antenna elevation power factor β_{Rv} and vertical beam width ψ_{v2} at the optimum elevation angle
64x39mm (300 x 300 DPI)



b The deviation of group delay resolution along with the transmitting antenna vertical beam width ψ_{v2} and receiving antenna vertical beam width ψ_{v1}, when receiving antenna height is $h_{re}=0$
66x41mm (300 x 300 DPI)

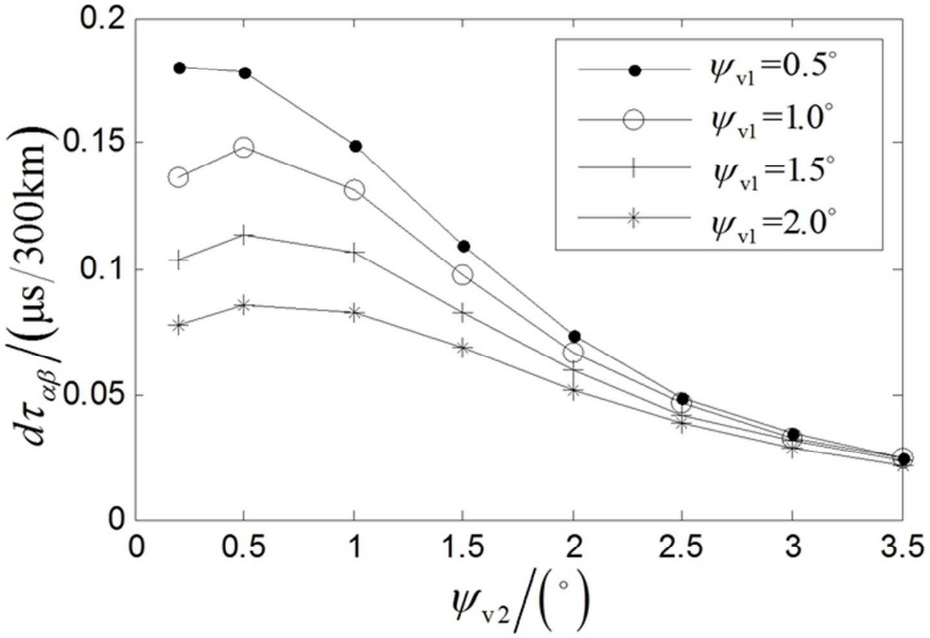


Fig. 8. The deviation of group delay resolution along with the transmitting antenna vertical beam width ψ_{v1} and receiving antenna vertical beam width ψ_{v2}, when receiving antenna height is h_{re}=1000m
63x42mm (300 x 300 DPI)