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ANTENNA DIRECTION-FINDING CHARACTERISTIC,(U)

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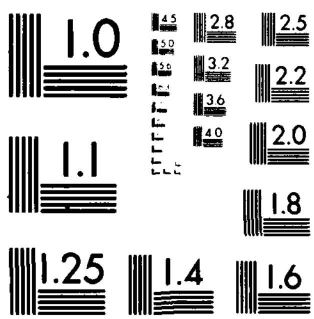

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ANTENNA DIRECTION-FINDING CHARACTERISTIC

by

V. G. Peshekhonov

FOREIGN TECHNOLOGY DIVISION

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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ANTENNA DIRECTION-FINDING CHARACTERISTIC

V. G. Peshekhonov

Summary

The side lobes of the direction-finding characteristic of a scanning antenna were studied. The connection between the statistical parameters of the directivity pattern and the direction-finding characteristic during a monochromatic and uncorrelated wide-band signal was determined. An integral parameter - the coefficient of scattering of the direction-finding characteristic - was introduced, and its values were estimated.

Introduction

During single-coordinate direction finding by successive amplitude comparison (scanning), the signal at the output of the goniometer is proportional to the value

$$G_n(\theta, \varphi) = G(\theta - \theta_{ск}, \varphi) - G(\theta + \theta_{ск}, \varphi), \quad (1)$$

where θ, ϕ are the angular coordinates of the source (θ is counted from the equisignal direction); θ_{CK} is half the scanning angle; $G(\theta, \phi)$ is the directivity pattern of the goniometer antenna.

The function $G_n(\theta, \phi)$ is usually called the direction-finding characteristic[1].

Footnote: [1]With two-coordinate scanning, two type [1] direction-finding characteristics are obtained independantly because of orthogonality. End footnote

Its value is of interest in different areas of radar [1], especially for goniometry of sources of incoherent (noise) emission. In the latter case, it completely determines the ratio of the useful signal to noise from external noise sources (background) [2]. The background consists of local and distant sources positioned randomly relative to the antenna. Therefore, it is necessary to have quantitative estimates of the direction-finding characteristic in the complete spatial angle. However, as far as this author knows, up to now direction-finding characteristics have only been studied near the equisignal direction.

The purpose of this study is to analyze the direction-finding characteristic in the vicinity of the side lobes. The specific properties of the noise emission sources - the signal bandwidth and the finite angular dimensions - were considered. The spatial structure was considered, and an integral parameter was introduced - the coefficient of scattering of the direction-finding characteristic. Calculated formulae and quantitative estimates of the parameters of the direction-finding characteristic were obtained for a mirror antenna based on the statistical description of its directivity pattern with a narrow-band [3] and a wide-band [4] signal.

Spatial Structure of Direction-Finding Characteristic

The analysis of the structure of the direction-finding characteristic and the calculation of its parameters are considerably simplified if we reduce the right side of formula (1) to the product of two functions, each of which depends only on one coordinate θ and ϕ. The derivation of an approximate formula of this type is given below for an axisymmetric direcitivty pattern and $\theta_{CK} \ll 1$ (a highly-directional antenna).

Suppose that scanning occurs relative to the z-axis in the plane $\phi=0$ (Fig. 1), so that the maximum of the pattern lies alternately on the axes z' and z". Along with angular coordinate system θ and ϕ bound to the z-axis, we will introduce the systems θ, ϕ and θ'', ϕ'', bound to the axes z' and z", respectively. Then, based on the assumption of the axial symmetry of the directivity pattern

$$G(\theta-\theta_{\text{ск}},\varphi)=G(\theta'),\ G(\theta+\theta_{\text{ск}}\varphi)=G(\theta''), \tag{2}$$

where the angles θ, ϕ, θ', θ'' satisfy the relationships of spherical triangles

$$\cos\theta'=\cos\theta_{\text{ск}}\cos\theta+\sin\theta_{\text{ск}}\sin\theta\cos\varphi,$$
$$\cos\theta''=\cos\theta_{\text{ск}}\cos\theta-\sin\theta_{\text{ск}}\sin\theta\cos\varphi. \tag{3}$$

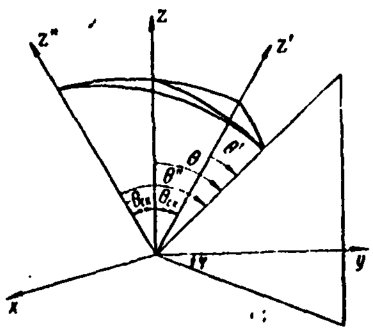

Fig. 1.

The right sides of formulae (3) can be approximately reduced to the cosines of several angles. Considering that $\theta_{ck} \ll 1$, we will set:

$$\cos\theta_{\text{ск}} \approx \cos(\theta_{\text{ск}}\cos\varphi), \quad \sin\theta_{\text{ск}}\cos\varphi \approx \sin(\theta_{\text{ск}}\cos\varphi). \tag{4}$$

The error in formula (3) when using approximate equations (4) is a value on the order of $0.5\,(\theta_{\text{ск}}\sin\varphi)^2$, i.e., there is no error in the scanning plane $\phi=0$, π, and in the plane $\phi=\pi/2$, $\frac{3}{2}\pi$, where it is the maximum, it does not exceed $\frac{\theta_{\text{ск}}^2}{2} \ll 1$.

With consideration of (4), formulae (3) assume the form

$$\theta' \simeq \theta - \theta_{\text{ск}}\cos\varphi, \quad \theta'' \simeq \theta + \theta_{\text{ск}}\cos\varphi. \tag{5}$$

The substitution of (5) in (2) and (1) gives us

$$G(\theta, \varphi) \approx G(\theta - \theta'_{\text{ск}}) - G(\theta + \theta'_{\text{ск}}), \tag{6}$$

where

$$\theta'_{\text{ск}} = \theta_{\text{ск}}\cos\varphi. \tag{7}$$

Expanding the function $G(\theta + \theta'_{\text{ск}})$ near point θ into a Taylor series

$$G(\theta + \theta'_{ck}) = G(\theta) + \theta'_{ck} G^{(1)}(\theta) + \frac{(\theta'_{ck})^2}{2} G^{(2)}(\theta) + \dots$$

and substituting this expansion in formula (6), with consideration of (7) we will have

$$G_n(\theta, \varphi) \approx -2 \sum_{m=1}^{\infty} \theta_{ck}^{2m-1} \cos^{2m-1}\varphi \, G^{(2m-1)}(\theta).$$

Because of the condition $\theta_{ck} \ll 1$, henceforth we will limit ourselves to only the first term in the series (theoretically, the consideration of the subsequent terms is not complex). Then

$$G_n(\theta, \varphi) \approx -2\theta_{ck} \cos\varphi \, G^{(1)}(\theta). \qquad (9)$$

As was anticipated, the direction-finding characteristic determined by (6) and (9) has even symmetry relative to the scanning plane ($\phi=0, \pi$) and odd - relative to the plane perpendicular to it $\left(\varphi = \frac{\pi}{2}, \frac{3}{2}\pi\right)$. According to (6) and (7), it suffices to know the direction-finding characteristic in the scanning plane and its dependence on the scanning angle in order to easily determine $G_n(\theta, \phi)$ in any plane ϕ=const. According to formula (9), it suffices to know the derivative of the directivity pattern for the approximate determination of $G_n(\theta, \phi)$.

It is also clearly evident from formula (9) that the direction-finding characteristic has a lobe structure with alternating positive and negative lobes. Remember that when incoherent emission is received, $G(\theta)$ is the directivity pattern for power, i.e., $G(\theta)\geqslant 0$.

Scattering Coefficient of Direction-Finding Characteristic

For a distant emission source, the signal at the goniometer outlet modulated at the scanning frequency is proportional to the integral of $G_n(\theta, \phi)$ taken from the spatial angle subtended by the source. Therefore, in order to estimated the modulated noises from external sources, we will introduce an integral parameter - the scattering coefficient of the direction-finding characteristic. We will define it analogously to the known antenna scattering coefficient (e.g., see [5]). The antenna scattering coefficient outside the spatial angle Ω

$$\beta=\int\limits_{4\pi-\Omega}\int G(\theta,\varphi)\,d\Omega=1-\int\limits_{\Omega}\int G(\theta,\varphi)\,d\Omega, \qquad (10)$$

where the directivity pattern (for power) $G(\theta, \phi)$ is normalized so that

$$\int\limits_{4\pi}\int G(\theta,\varphi)\,d\Omega=1. \qquad (11)$$

It is usually assumed that $\Omega=\Omega_{гл}$ is the spatial angle which subtends the main lobe of the directivity pattern.

Introducing the scattering coefficient of the direction-finding characteristic ($\beta_{п}$) analogously to (10), it is necessary to consider the odd symmetry of $G(\theta, \phi)$ relative to the plane $\varphi=\frac{\pi}{2}, \frac{3}{2}\pi,$ as a result of which sources positioned symmetrically relative to this plane to not emit a signal which is modulated at the scanning frequency. Therefore, we will define $\beta_{п}$ as follows:

$$\beta_{п}=\int\limits_{\varphi_1}^{\varphi_2} d\varphi \int\limits_{\theta_1}^{\theta_2} G(\theta, \varphi)\sin\theta\, d\theta, \tag{12}$$

where

$$-\frac{\pi}{2}\leqslant\varphi_1<\varphi_2\leqslant\frac{\pi}{2}, \quad \theta_{гл}\leqslant\theta_1<\theta_2\leqslant\pi;$$

$\theta_{гл}$ is the angle which determines the position of the first zero (or minimum) of the directivity pattern.

Substituting (9) in (12) and integrating (we will take the integral with respect to θ "by parts"), we will have

$$\beta_{п}=2\theta_{ск}(\sin\varphi_2-\sin\varphi_1)\left[G(\theta_1)\sin\theta_1-G(\theta_2)\sin\theta_2+\int\limits_{\theta_1}^{\theta_2} G(\theta)\cos\theta\, d\theta\right]. \tag{13}$$

Subsequently, we will consider the partial case when scattering is determined outside the main lobe of the directivity pattern.

Setting $\phi_1=\pi/2$, $\phi_2=\pi/2$, $\theta=\theta_{гл}$, $\theta=\pi$, respectively, in (13), and considering that $G(\theta_{гл})=0$, we will have

$$\beta_n = 4\theta_{ск} \int_{\theta_{гл}}^{\pi} G(\theta)\cos\theta\, d\theta. \qquad (14)$$

The peculiarity of (14) compared to (10) is that in subintegral expression (14), $\sin\theta$ is replaced by $\cos\theta$. As a result, we cannot automatically reduce (14) to the calculation of the integral from the directivity pattern $G(\theta)$ in the vicinity of the main lobe, as is done in (10). It is necessary to integrate $G(\theta)\cos\theta$ in the angle $\theta_{гл}\leqslant\theta\leqslant\pi$, where known difficulties are encountered in determining $G(\theta)$. This problem is considered in the next section of the report.

It is not difficult to establish the relationship between β_n and β. From (14) and (10) we have

$$\frac{\beta_n}{\beta} = \frac{2\theta_{ск}}{\pi} \frac{\int_{\theta_{гл}}^{\pi} \cos(\theta)\cos\theta\, d\theta}{\int_{\theta_{гл}}^{\pi} G(\theta)\sin\theta\, d\theta}. \qquad (15)$$

A linear dependence on θ is characteristic of formulae (14) and (15). Since $\theta_{ск}<<1$, $\theta_{гл}<<1$, $\beta_n<<\beta<<1$.

Whence the antenna noise component modulated at the scanning frequency is considerably smaller than the constant component. This is due to the situation mentioned at the end of the preceding section: all of the lobes of pattern $G(\theta)$, which determine the value of β, are inphase, while lobes $G_n(\theta, \phi)$ are sign-variable.

Statistical Parameters of the Direction-Finding Characteristic

The formulae obtained above make it possible to calculate the direction-finding characteristic and its scattering coefficient if we know the directivity pattern $G(\theta)$ in the entire spatial angle. The problem is that the directivity pattern of most SHF antennae cannot be calculated in the vicinity of the far side lobes. One possible way of dealing with this problem is to use the statistical description of $G(\theta)$. Report [3] shows that the directivity pattern of a mirror antenna in the vicinity of the irregular (far) lobes can be considered to be a stationary random process which is nearly Gaussian. Obviously, the processes $G(\theta-\theta_{CK})$ and $G(\theta+\theta_{CK})$ and, consequently, also the direction-finding characteristic, can also be considered to be nearly Gaussian processes.

We will designate the mathematical xpectation and dispersion of the process $G(\theta)$ as m and σ^2, respectively. Based on stability at a fixed ϕ

$$M[G(\theta-\theta_{c\kappa})] = M[G(\theta+\theta_{c\kappa})] = m, \quad (16)$$

$$D[G(\theta-\theta_{c\kappa})] = D[G(\theta+\theta_{c\kappa})] = \sigma^2. \quad (17)$$

Since $G_n(\theta)$ is a Gaussian process, its distribution is completely determined by two parameters: mathematical expectation (m_n) and dispersion (σ_n^2). Considering (16) and (17), we will have:

$$m_{п} = M[G(\theta+\theta_{ск})] - M[G(\theta-\theta_{ск})] = 0, \quad (18)$$

$$\sigma_{п}^2 = D[G(\theta+\theta_{ск})] + D[G(\theta-\theta_{ск})] - 2\sigma^2 K(2\theta_{ск}) = 2\sigma^2[1-K(2\theta_{ск})], \quad (19)$$

where $K(\theta_{\tau})$ is the autocorrelation coefficient of process $G(\theta)$.

According to (18) and (19), in a fixed plane ϕ=const, $G(\theta)$ is a stationary Gaussian process with a zero mean value and dispersion which depends on the scanning angle. The autocorrelation coefficient of the directivity pattern measured with respect to power is essentially equal to zero when $\theta_{ck}>\theta_0$ [3]. Therefore, according to (19), the dispersion of the direction-finding characteristic when $\theta'_{ck}>\theta_0$ is equal to twice the dispersion of the directivity pattern. It is necessary for angle θ'_{ck} to be sufficiently small so that $\sigma_n^2<\sigma$. As ϕ increases from 0 to $\pi/2$, θ'_{ck} and, consequently, also the lobes of the direction-finding characteristic decrease; process $G(\theta, \phi)$ is unstable with respect to ϕ.

In order to calculate the scattering coefficient of the direction-finding characteristic, we will divide the integration interval in (14) into two parts: $\theta_{гл} \leqslant \theta \leqslant \theta_{р}$ and $\theta_{р} \leqslant \theta < \pi$ (here $\theta_{р}$ is the boundary of the regular and irregular lobes). In the first part of the interval, there is no major problem with integration. Since the antenna is highly-directional and $\theta_{гл} \ll 1$, $\theta_{р} \ll 1$,

$$\int\limits_{\theta_{гл}}^{\theta_{р}} G(\theta)\cos\theta\, d\theta \approx \int\limits_{\theta_{гл}}^{\theta_{р}} G(\theta)\, d\theta \quad (\theta_{р} - \theta_{гл}) m_{р}, \tag{20}$$

where $m_{р} = \dfrac{\int\limits_{\theta_{гл}}^{\theta_{р}} G(\theta)\, d\theta}{\theta_{р} - \theta_{гл}}$ is the mean level of the regular lobes.

We will estimate the integral from the second part of the interval by using the statistical representation of $G(\theta)$. Considering that with sufficient directivity of the antenna, $G(\theta)$ changes rapidly compared to $\cos\theta$ of the function, and that the sign of $\cos\theta$ changes in the interval $(\theta_{р}, \pi)$, we will obtain the estimate

$$\int\limits_{\theta_{р}}^{\pi} G(\theta)\cos\theta\, d\theta \approx -m\theta_{р}. \tag{21}$$

Since $m_{р} \gg m$, the regular lobes of the pattern make the main contribution to the value of the scattering coefficient of the direction-finding characteristic, and (14) can be written as

$$\beta_{п} \approx 4\theta_{ск}(\theta_{р} - \theta_{гл}) m_{р}. \tag{22}$$

According to (22), in order to estimate the scattering coefficient of the direction-finding characteristic, it suffices to know only the parameters which are either easy to calculate or easy to determine experimentally. Like the level of the side lobes, the value of β_n decreases as $\theta_{ск}$ decreases. β_n does not depend on the directivity of the antenna - the values $\theta_{ск}$, θ_p, and $\theta_{гл}$ are proportional to θ_0, and with consideration of (11), the value of m_ρ is proportional to θ_0^{-2}.

Calculations made using formula (22) give us the value β_n=1.3o/o with a uniform field distribution in the antenna aperture and β_n=0.2o/o with zero illumination of the edge.

It is more complex to experimentally determine β_n than β. In fact, while it is easy to calculate the value of β from the measured increment in antenna noise from a "black" disk which covers the main lobe of the directivty pattern [5], we need a "black" disk which subtends almost half the spatial angle $\left(-\frac{\pi}{2}\leqslant\varphi\leqslant\frac{\pi}{2},\ \theta_{гл}\leqslant\theta\leqslant\pi\right)$ in order to find β_n. It is expedient to use the underlying surface as this disk. However, one must consider that in this case, the main lobe of the directivity pattern will scan near the horizon, where the maximum atmospheric brightness occurs. Therefore, it is necessary to exclude the modulated noise of the antenna caused by scanning of the main lobe from the results. This noise is not difficult to calculate for decimeter waves, and also for centimeter waves with a homogeneous atmosphere. Additional sources of experimental error are the irregular brightness temperature of the underlying surface across the angle and its location in the far or intermediate zone of the antenna. These errors are especially large in the vicinity of the near side lobes of the directivity pattern.

Measurements of β_n were taken in order to minimize these errors. A parabolic mirror with an aperture diameter of 30 wavelengths was installed so that the equisignal direction formed an angle of 12° to the plane of the horizon and the near side lobes were directed to the framework. A sufficiently large angle of elevation made it possible to calculate the modulated noise caused by scanning of the main lobe of the directivity pattern.

After eliminating the effect of the atmosphere, when θ_{ck} =0, 016, the value of β_n was 2.6o/c. For the same antenna, β=21o/c. The divergence of these experiments from the previous calculated estimates is caused first by the fact that the estimates were made in the aperture approximation and did not consider many factors, and second, because the aberrations which occur during scanning were not considered. However, it is significant that like the calculation, the experiment confirmed the inequality $\beta_n \ll \beta$. Furthermore, a nearly linear dependence $\beta_n(\theta_{ck})$ was found, which corresponds to formula (22). Thus, when θ_{ck} increased 1.27 times, coefficient β_n increased

1.21 times. The experiment made it possible to estimate the contribution of the near and far side lobes to the value of β_n. Increasing the angle between the equisignal direction and the plane of the horizon to 25°, when the regular lobes turned out to be directed toward the sky, caused β_n to be reduced to 0.3o/o. Finally, the experimental data agreed well with the result of the calculation of β_n from formula (15). Using this formula for the numerical integration of the experimental directivity pattern gave us the value β_n=2.9o/o.

Parameters of Direction-Finding Characteristic During a Wide-Band Signal

When the receiver has a finite passband, the angular sensitivity of the antenna relative to uncorrelated signals is determined by the directivity pattern (characteristic) averaged over the passband of the receiver:

$$\Phi(\theta)=\frac{\int\limits_{-\infty}^{\infty} S(\omega)G(\theta,\ \omega)\,d\omega}{\int\limits_{-\infty}^{\infty} S(\omega)\,d\omega}, \qquad (23)$$

where $S(\omega)$ is the frequency characteristic of the HF filter of the receiver.

Report [4] shows that for a reflector antenna, in the vicinity of the far side lobes, the pattern $\Phi(\theta)$ can be considered to be an unstable Gaussian process with a constant mathematical expectation and dispersion which decreases as angle θ increases. This gives us grounds for considering the direction-finding characteristic during a wide-band signal to be a Gaussian process. Obviously, its mathematical expectation is equal to zero. The dispersion is calculated from a formula of the type (19), where it is necessary to substitute $\Phi(\theta)$ for $G(\theta)$. We will consider its terms.

According to report [4], with sufficiently large values of θ

$$D[\Phi(\theta\pm\theta_{c\kappa})] \simeq 2\sigma^2\left[\frac{1}{2\pi a(\theta\pm\theta_{c\kappa})} - \frac{1}{(2\pi a)^2(\theta\pm\theta_{c\kappa})^2}\right], \qquad (24)$$

where a is the parameter of the autocorrelation function of the directivity pattern [4]:

$$R(t,t') = \sigma^2 e^{-a|t-t'|},\quad t = \theta_1\frac{\omega}{\omega_0},\quad t' = \theta_2\frac{\omega'}{\omega_0},\quad a>1. \qquad (25)$$

Considering that in the vicinity of the irregular lobes, $\theta >> \theta_{c\kappa}$, from (24) we have

$$D[\Phi(\theta-\theta_{c\kappa})] + D[\Phi(\theta+\theta_{c\kappa})] \approx \sigma^2\frac{2\pi a\theta-1}{(\pi a\theta)^2}. \qquad (26)$$

It is not difficult to show that in the problem in question, the relationship between the autocorrelation coefficients of the directivity pattern and characteristic is given by the formula

$$K_{\Phi}(\theta_1, \theta_2) = \frac{1}{\left|\int\limits_{-\infty}^{\infty} S(\omega)\, d\omega\right|^2} \int\limits_{-\infty}^{\infty}\int S(\omega)\, K\left(\theta_1 \frac{\omega}{\omega_0},\ \theta_2 \frac{\omega'_1}{\omega_0}\right) d\omega' d\omega. \quad (27)$$

For definiteness, we will assume that the characteristic of the HF filter is rectangular:

$$S(\omega) = \begin{cases} 0 & \omega \leqslant \omega_0 (1-n), \\ 1\ \omega_0(1-n) \leqslant & \omega \leqslant \omega_0 (1+n), \\ 0 & \omega \leqslant \omega_0 (1+n) \end{cases}$$

and that $\theta_1=\theta$, $\theta_2=\theta+2\theta_{CK}$.

Then, integrating (27), we will have

$$K_{\Phi} \simeq \frac{2a^2}{x^2}\left[x + (e^{-x} - 1)\, \mathrm{ch}\, 2a\theta'_{\text{ск}}\right], \quad (28)$$

where we have designated x=2 naθ. With sufficiently large θ, so that x>>1,

$$K_{\Phi} \simeq \frac{2a^2}{x^2}(x - \mathrm{ch}\, 2a\theta'_{\text{ск}}). \quad (29)$$

Substituting (29) and (26) into formula (19), we will have

$$\sigma_n^2 \simeq 4\sigma^2 \frac{\mathrm{ch}\,2a\theta'_{CK} - 1}{\Lambda^2}. \qquad (30)$$

Like for a narrow-band HF filter, σ_n^2 increases as θ_{CK} increases (we should consider that formula (30) was obtained with the assumption that $\theta_{CK} \ll 1$ and $\mathrm{ch}2a\theta_{CK}$ is a limited value). The significant difference is that with a wide-band signal, the dispersion of the direction-finding characteristic decreases as θ increases. Thus, in this case, the direction-finding characteristic is an unstable Gaussian process with a zero mathematical expectation and dispersion which decreases as angle θ increases. The value of σ_n is inversely proportional to the relative band (2 n) of the HF filter. Therefore, broadening the band of the HF filter reduces the level of the side lobes of the direction-finding characteristic.

The scattering coefficient of the direction-finding characteristic depends little on the band of the HF filter, since it is determined by the regular side lobes, whose mean level essentially does not depend on the band.

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