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THE USAGE FEATURES OF MULTIFREQUENCY SPACE-TIME SIGNALS IN SUPER-FAST SCANNING RADAR WITH ACTIVE PHASED ANTENNA ARRAY

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Abstract

The usage features of multifrequency (MF) space-time signals (STS) which are formed by transmitter active phased antenna array (APAA) radar with angular super fast scanning (STS) in with paper are examined. The STS structural, correlation features and its interrelation with parameters of MF modulation and APAA characteristics are determined. It is shown that the usage of complex partial signal in each radiation element in association with suitable partial waveform can realize a synthesis (reconstruction) of transmitter APAA directional characteristic in receiver by returned signals. Reliability of the results is confirmed by simulation modeling on different partial signals.

Keywords: antenna array, multifrequency space-time signals, super fast scanning radar.

1. INTRODUCTION

The perspective field in the antennal theory and techniques development is related to the development of the APAA which improve the radar performance by using space STS [1] and synthesis (reconstruction) of the transmitting arrays directional pattern (DP) in the receiver by reflected signals [2,3,4]. The selection of the STS requires the knowledge of the dependencies between antenna parameters, properties, and the structure of the probe signals. Since using MF modulation possesses advantages in realization of STS in the APAA (radiators matching, antenna efficiency, etc.), thus it is necessary to determine dependencies between the structure, correlation properties of the MF STS, modulation parameters in the APAA, and its parameters.

2. ANALYSIS RESULTS OF THE MF STS

In general case we can write MF modulation function in the APAA as:

$$\dot{T}_{MF}(t) = e^{j(2\pi f_0 t + \varphi_0)} \sum_{n=-N}^{N} \dot{T}_n(t) = \sum_{n=-N}^{N} T^0(t) \cdot \dot{A}_n e^{j2\pi p_n \Delta f t}, \quad (1)$$

where $\dot{T}_n(t)$ is a complex envelope (CE) of the partial components are fed to each of n-th of the $2N+1$ radiating elements; f_0, φ_0 are mean frequency and initial phase; $\Delta f = T^{-1} = f_o \gamma^{-1}$, $(\gamma >> 1)$ is a frequency shift between $\dot{T}_n(t)$; $\dot{A}_n \in \dot{A}(n)$, $p_n \in p(n) \in (-N; N)$, are the weighting function (WF) and the frequency distribution (FD). Consider linear equidistant transmitting array of $2N+1$ equally-oriented non-interacting radiators with independent of frequency DP $f(\tilde{\theta})$ Fig. 1. The STS is provided by FD in APAA [4]:

$$p_n = n \in (-N; N), \quad p_n = n \in (N; -N). \quad (2)$$

We separate MF STS depending on $T^0(t)$ form on - continuous - $T_C^0(t) = \text{const}, \forall t$; simple impulse - $T_{SI}^0(t) \neq 0 = \text{const}$, $|t| \leq 0{,}5\tau_S = 0{,}5KT$, and complex - $T_{CI}^0(t) \neq 0 = \text{var}$, $|t| \leq 0{,}5KT$. Thus STS in accordance with (1) we consider as narrow-band.

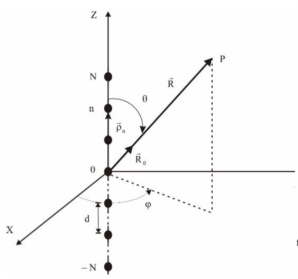


Fig. 1. APAA model.

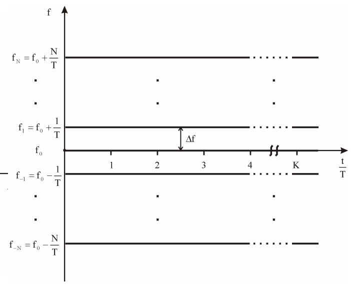


Fig. 2. Components of STS.

2.1. CONTINUOUS MF STS

Generated STS (Fig. 2.) and its spectrum in point P equals with a constant precision to:

$$\dot{E}_C(\tilde{\theta}, t') = f(\tilde{\theta}) \sum_{n=-N}^{N} \dot{A}_n \exp\{j2\pi p_n \Delta f t'\} \cdot e^{j2\pi \frac{d}{\lambda_0} n \cos\tilde{\theta}};$$

$$\dot{E}_C^f(\tilde{\theta}, 2\pi f, \tilde{t}_D) = 2\pi f(\tilde{\theta}) e^{-j2\pi f \tilde{t}_D} \sum_{n=-N}^{N} \dot{A}_n \delta[2\pi(f - p_n \Delta f)] e^{j2\pi \frac{d}{\lambda_0} n \cos\tilde{\theta}} \quad (3\text{ b})$$

where $t' = t - |\tilde{\vec{R}}| c^{-1}$ is a time with delay $\tilde{t}_D$ in the point with vector-radius $\tilde{\vec{R}}$; $\lambda_0 = c f_0^{-1}$.

According to (3) for FD (2) and $\dot{A}_n = A_n \geq 0$, the absolute maximum of the STS on a space-time plane exists if the following equation is satisfied:

$$2\pi(\pm tT^{-1} \mp |\tilde{\tilde{R}}|\, \Delta\lambda^{-1} + d\lambda_0^{-1}\cos\tilde{\theta}) = \pm 2m\pi, \qquad (4)$$

where $\Delta\lambda = c\Delta f^{-1}$; $m = 0,1,2...$.

Distribution of the STS maximum of order m and condition of its existence for real $\tilde{\theta}$:

$$\tilde{\theta}_m(t) = \arccos\frac{\lambda_0}{d}\left(m \mp \frac{t}{T} \pm \frac{|\tilde{\tilde{R}}|}{\Delta\lambda}\right); \left|\frac{\lambda_0}{d}\left(m \mp \frac{t}{T} \pm \frac{|\tilde{\tilde{R}}|}{\Delta\lambda}\right)\right| \le 1. \qquad (5)$$

Distribution (5) is periodical because of discrete behavior of the emitting system and the signal spectrum. T - determines the periodicity in time (distance); by the angle $\tilde{\theta}$ - the electrical size of the APAA - $d\lambda_0^{-1}$. However, the «illumination» period - time which takes for the m-th maximum to pass the visibility scope is connected with the parameters of APAA as:

$$T_{ill} = 2Td\lambda_0^{-1}. \qquad (6)$$

For $2d\lambda_0^{-1} > 1$, $T_{ill} > T$, the neighboring maximums of the STS are overlapping in time. As an example on Fig. 3. it is shown a normed module of the STS which is formed by the linear equidistant APAA, constructed of the electric dipoles, for FD (2).

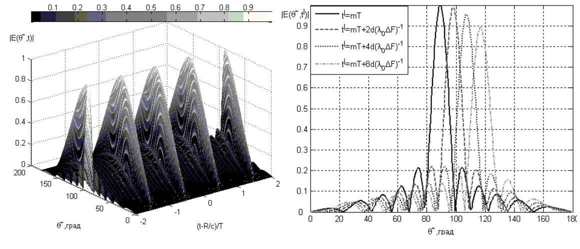


Fig. 3. The STS module.

The dependencies are obtained for $t' \in 2(-T;T)$, $\Delta f = f_0 10^{-4}$, $2N+1 = 11$, $d = 0{,}5\lambda_0$, $\dot{A}_n = 1$. The STS maximum passes over the distance $\Delta\lambda$ in time T. At times $t' \in mT$, $m = 0,1,2....$ the maximum is oriented by the normal to the APAA axis, its width in planes $\tilde{\theta}$ and t' is determined as $\theta^{STS} = C_\theta^w \lambda_0 L^{-1}$ and $\tau^{STS} = C_\tau^w \Delta F^{-1} = C_\tau^w/(2N+1)\Delta f$ respectively, where $C_\theta^w, C_\tau^w > 0$ depend on WF. Thus, the signal is "compressed" in time in the space because of the common-mode summation of it partial components. This allows us to relax constrains on the peak power of the impulse signals quasi-continuously emitted by the APAA components. The STS maximum by angle $\tilde{\theta}$ is translated on level -3dB in widths in time $t_0 = 2d(\lambda_0\Delta F)^{-1}$, (Fig. 3). Thus, in the radiation interval an infinite number of instantaneous DPs are formed in space, and the number of resolving equals to $T_{ill}t_0^{-1} = 2N+1$. For FD (2) the dependency on $\tilde{\theta}$ of the STS phase-frequency spectrum in angle range is close to linear. This allows us to eliminate multiple channels of the processing units for a specific angular coordinates of the sources of signals reflected relatively to the transmitting APAA in a wide sector if the direction corresponding to the radiation by a normal to the array is used as expected angular direction (reference signal).

Space-time correlation function (STCF) of the signal (a delay time relatively to the transmitting APAA in the elevation plane) for DP (2) and $\theta = 0{,}5\pi$ takes the form:

$$\dot{K}_C(\tilde{\theta},\tau) = f(\tilde{\theta})\sum_{n=-N}^{N}\left|\dot{A}_n\right|^2 \cdot e^{-j2\pi\frac{d}{\lambda_0}n(\cos\theta-\cos\tilde{\theta})}\, e^{j2\pi n\Delta f\tau}. \qquad (7)$$

where θ is the expected angle of arrival; τ is the temporal unbalance parameter.

The condition of existence of the absolute maximum of STCF of order m in the plane τ and its distribution on the space-time plane:

$$(d\lambda_0^{-1}\cos\tilde{\theta} \pm \tau T^{-1}) = \pm m; \tau_m(\tilde{\theta}) = \pm T(d\lambda_0^{-1}\cos\tilde{\theta} \mp m). \qquad (8)$$

The period of the «observation» (time which takes for the m-th maximum of STCF to pass over the APAA visibility scope region):

$$T_{obs} = T_{ill} = 2Td\lambda_0^{-1}. \qquad (9)$$

For $2d\lambda_0^{-1} > 1$, $T_{obs} > T$, adjacent maximums are overlapping in time and the period of unambiguous detection of angle of the target on the delay time of the STCF maximum on the output of the processing unit relatively to the transmitting APAA is decreasing. Since $d < 0{,}5\lambda_0$ is hard to achieve, it is reasonable to decrease the scanning time of the space (T_{obs}, T_{ill}) at the expense of increase in Δf. Normalized modulus of STCF is shown on Fig. 4 for $\theta = 0{,}5\pi$ and the data chosen above.

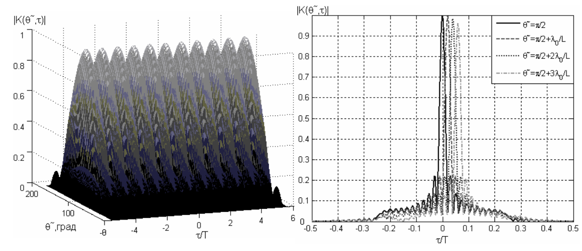
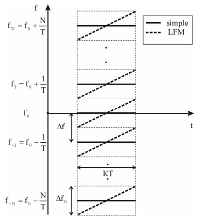


Fig. 4. STCF of the signal.

STCF structure has multiple peaks and the position of the maximums by τ depends on the target position $\tilde{\theta}$ (8). For $\theta = \tilde{\theta}$ the width of the maximum STCF equals to $\tau^{STS} = C_\tau^w \Delta F^{-1}$. In correspondence with (8), (9) and Fig. 4 the relative shift of the STCF envelope in the ranges of T_{obs} by the value $\tau_0 = 2d/(\lambda_0\Delta F)$ corresponds to the change in $\tilde{\theta}$ of the target by the value of maximum $\theta^{STS}(mT)$. For the period $\tau \in n(-Td\lambda_0^{-1}; Td\lambda_0^{-1})$, $n \in (-N;N)$ an infinite number of synthesized (reconstructed) DPs of the emitting APAA are formed in the receiver, $T_{obs}/\tau_0 = 2N+1$ of which can be resolved. Thus, it is possible to obtain the angular position of the target relatively to the transmitting APAA only during an unambiguous period (with uncertainty in distance-angle) by the estimation of the maximal STCF delay time relatively to the reference signal.

2.2. Impulse MF STS

For the simple impulse MF STS (Fig. 5.) equations (4)-(6) hold true considering $t' \in 0{,}5(-KT; KT)$.



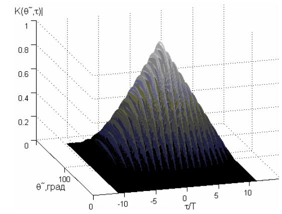


Fig. 5. STS components. **Fig. 6.** STCF $K = 11$

Finite burst mode STS is formed in the radiation zone. For $d\lambda_0^{-1} = 0{,}5$ the number of impulses in burst and its duty factor: $N_{imp} = \tau_s \Delta f = K$, $Q = T/\tau^{STS} = (2N+1)/C_t^W$. Corresponding to (5) we can exclude grating lobes of the STS for $1 > d\lambda_0^{-1} > 0{,}5$ by τ_S choosing. Spectral density with duty factor $Q^f = K^{-1}$ and STCF for $\theta = \pi/2$ equal to:

$$\dot{E}_{SI}^{f}(\tilde{\theta}, 2\pi f, \tilde{t}_D) = \frac{K}{\Delta f} f(\tilde{\theta}) e^{-j2\pi f \tilde{t}_D} \sum_{n=-N}^{N} \dot{A}_n \,\mathrm{sinc}\left[K\pi(f - p_n)\right] e^{j2\pi n \frac{d}{\lambda_0} \cos\tilde{\theta}}$$

$$\dot{K}_{SI}(\tilde{\theta}, \tau) = \dot{K}_{SI}^{0}(\tau) \dot{K}_C(\tilde{\theta}, \theta, \tau),$$

where $\dot{K}_{SI}(\tau) = KT(1 - |\tau|(KT)^{-1})$ is autocorrelation function (ACF) of the central signal partial component. For $K > 1$ the STCF (Fig. 6) has multiple peaks, and the position of the maximums by τ depends on the target $\tilde{\theta}$ (8) and the signal correlation property coincides with continuous MF STS over a period T_{obs}. Thus, by using impulse STS with a discrete spectrum we can obtain the angular position of the target only on the unambiguous interval T_{obs}. We can also obtain the distance by the STCF envelope on the output of the processing unit with a resolution equal to $\delta r = 0{,}5c\tau_c = 0{,}5cKT$. For $K \leq 1$ the STS spectrum is continuous, the period of the signal and STCF in time (distance) are eliminate, however there is an uncertainty in angle-delay plane Hence, a contradiction between scanning time and an interval of unambiguous detection of the angle coordinate on one side and the resolution in distance and signal duration on the other side is an inherent part of this signal. By increasing in τ_s the amplitude-frequency spectrum (AFS) width of the component is decreasing, but the duty factor of the total AFS is increasing. The conformance can be resolved by the use of the partial signals with AFS width almost independent of the duration and specific parameters satisfying the condition on AFS of the partial components being adjacent. This is possible if the complex signals are considered as partial components, e.g. a chirp for $\dot{T}_{LFM}^{0}(t) = \exp\{j\pi b t^2\}$ and $b = \Delta f \tau_s^{-1}$ Fig. 5. STS, its spectral density and STCF for $\theta = 0{,}5\pi$ can be written as:

$$\dot{E}_{LFM}(\tilde{\theta}, t') = f(\tilde{\theta}) \sum_{n=-N}^{N} \dot{A}_n \exp\{j2\pi(p_n \Delta f t' + 0{,}5 b t'^2)\} e^{j2\pi n \frac{d}{\lambda_0} \cos\tilde{\theta}};$$

$$\dot{E}_{LFM}^{f}(\tilde{\theta}, 2\pi f, \tilde{t}_3) = T\sqrt{2K} e^{-j2\pi f \tilde{t}_3} f(\tilde{\theta}) \sum_{n=-N}^{N} \dot{A}_n \cdot e^{j2\pi n \frac{d}{\lambda_0} \cos\tilde{\theta}} \times$$

$$\times \sqrt{(C(x_2) + C(x_1))^2 + j(S(x_2) + S(x_1))^2} \times$$

$$\times \exp\left\{ j\left[K\pi(p_n - fT)^2 + \mathrm{arctg}\left(\frac{S(x_2) + S(x_1)}{C(x_2) + C(x_1)} \right) \right] \right\};$$

$$\dot{K}_{LFM}(\theta, \tilde{\theta} = 0{,}5\pi, \tau) = \dot{K}_{LFM}^{0}(\tau) \dot{K}_C(\tilde{\theta}, \theta, \tau),$$

where $S(x), C(x)$ are sine and cosine Fresnel integrals; $x_{1,2} = \sqrt{\pi b}\left(\mp 0{,}5\tau_c + b^{-1}(p_n \Delta f t - f)\right)$; $\dot{K}_{LFM}^{0}(\tau) = \dot{K}_{SI}^{0}(\tau) \sin c[\pi\tau\Delta f(1 - |\tau|(KT)^{-1})]$ are a ACF of the central chirp partial.

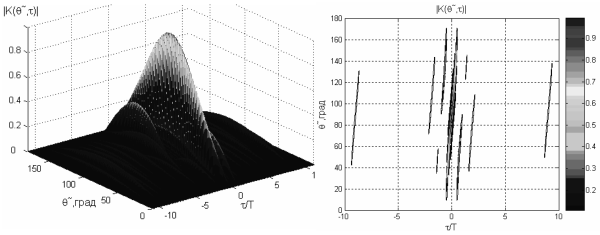


Fig. 7. Normalized module of STCF $K = 11$, $b = \Delta f \tau_s^{-1}$.

STCF parameters (Fig. 7) near the main maximum are close to the parameters of the continuous MF STS on the interval T_{obs}. Resolution in the distance does not depend on the signal duration $\delta r = cC_\tau^W / 4\Delta F$ and is determined by the total bandwidth, i.e. the number of frequency components (APAA radiators).The time of the scanning (T_{ill}, T_{obs}) is determined only by Δf and the array step $d\lambda_0^{-1}$. Hence, the use of signal allow to overcome the conformances between the scanning time, interval of the unambiguous detection of the angle and resolution in distance. The processing unit can have a single or few channels on the input angle and can be built of standard components and devices (spectral or temporal correlators) because of the synthesis (reconstruction) of the transmitting APAA DP in the receiver when using the signal, corresponding to the normal of APAA as the reference signal. The drawbacks of the signal include high level of the far-out sidelobes of STCF for the input angles deflected from normal (approximately -16dB for most symmetrical WF).

3. Conclusion

The presented results can be used to select the STS in order to increase the scanning rate using the super fast scanning radars with APAA.

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