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IMPACT OF THE ADC CLOCK PERIOD INSTABILITY ON THE ANGULAR ACCURACY OF THE LINEAR DIGITAL ANTENNA ARRAY

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The non-synchronous triggering of analog-to-digital converters (ADC) in terms of the array of primary channels is one of the sources of instrumental errors in digital antenna arrays (DAA). However, under the time-stationary state conditions the digitization timing violations can be easily compensated by the correction of characteristics of DAA receiving channels [1]. In the case of unpredictable fluctuations of the time location of pulses of the ADC clock period (e.g., in the case of the fiber optic lay-out due to the response time variation of photodetectors [2]) the errors of spatial discretization occur that cannot be eliminated by the correction algorithms. The only possibility to maintain the acceptable quality level of DAA operation is to limit dispersions of fluctuations of clock pulse arrival times at the maximum admissible level. The purpose of the present paper is to obtain an estimate of this level using the statistical simulation results.

Let us consider the DAA model for a linear equidistant array consisting of R elements with identical directivity characteristics. The output voltages of R receiving channels under the conditions of the echo-signal of a single point source being applied to the DAA input can be expressed in the form of the following set of R voltages with due regard for the ADC non-synchronous triggering:

$$\dot{U}_r = U_r^c + j\,U_r^s = \dot{a}\,\dot{F}_r \exp(j\,x_r) + \dot{n}_r = [a^c F_r^c - a^s F_r^s] \cos x_r - \sin x_r \times$$
$$\times [a^s F_r^c + a^c F_r^s] + j\,\{[a^c F_r^c - a^s F_r^s] \sin x_r + [a^s F_r^c + a^c F_r^s] \cos x_r\} + \dot{n}_r, \tag{1}$$

where $\dot{F}_r = F_r^c + j\,F_r^s$ is the complex directivity characteristic of the r-th receiving channel; $\dot{a} = a^c + j\,a^s$ is the complex amplitude in the bench-mark channel; $x_r = x\,(r - z) + \xi_r$; z is the point coordinate at the antenna aperture, selected as the array phase center; ξ_r is the signal phase distortion in the r-th channel due to the non-accounted fluctuations of its digitizing times; $x = \frac{2\pi}{\lambda}\,d \sin\theta$ is the generalized angular coordinate of the source; λ is the wavelength; d is the array pitch; θ is the angle between the direction at the source and the normal to the array; $\dot{n}_r$ is the complex value of noise in the r-th channel.

With respect to noises we can assume that they are Gaussian, uncorrelated and have zero average values and identical variances of quadrature components σ_n^2 in each specific channel.

Let us specify the normal distribution law of the random uncorrelated value ξ_r that characterizes the variation of ADC triggering time over the DAA sheet, designating its dispersion as σ_ξ^2. To analyze the quality of DAA operation, let us use the measurement procedure performing the function maximization (by the exhaustive search for possible values of the generalized angular coordinate x):

$$L_\text{M} = [\tilde{U}^{c^2} + \tilde{U}^{s^2}] \left(\sum_{r=1}^{R} [F_r^{c^2} + F_r^{s^2}] \right)^{-1} = \max, \tag{2}$$

Table 1

R	$\frac{a}{\sigma_n} = 4, \sigma_\xi = 0.314$	$\frac{a}{\sigma_n} = 2, \sigma_\xi = 0$
16	0.06285	0.06686
64	0.03279	0.03885

where $\widetilde{U}^c = \sum\limits_{r=1}^{R} \left\{U_r^c \,[F_r^c \cos x_r - F_r^s \sin x_r\,] + U_r^s \,[F_r^s \cos x_r + F_r^c \sin x_r\,]\right\}$,

$$\widetilde{U}^s = \sum_{r=1}^{R} \left\{U_r^s [F_r^c \cos x_r - F_r^s \sin x_r\,] - U_r^c \,[F_r^s \cos x_r + F_r^c \sin x_r\,]\right\}.$$

Such an approach is preferable, because relationship (2) represents a likelihood function option modified as described in paper [3] that enables us to ensure the potential accuracy of direction finding. In this case, the standard deviation (SD) of the angular coordinate estimate σ_x can be used as a quality indicator. As for fluctuations of the digitization times, it is expedient to refer their SD to the value of carrier f_0 for which analog-to-digital conversion of signals is performed. Their reference to the ADC clock period Δt would have been too abstract.

We can assume that the required relationship between Δt and f_0 has the form $2\pi f_0\, \Delta t = \pi / 2$, i.e., digitizing can be performed at a quarter of the carrier period. Then, $\sigma_\xi = 2\pi f_0\, \sigma_{\Delta t}$, where $\sigma_{\Delta t}$ is the SD scattering of the ADC triggering times; in this case, the SD is the same for all receiving channels.

To comprehensively study the impact of chaotic timing violations in the array, the statistical simulation was conducted for three different cases: 1) $\sigma_\xi \neq 0$, $\sigma_n = 0$; 2) $\sigma_\xi = 0$, $\sigma_n \neq 0$; 3) $\sigma_\xi \neq 0$, $\sigma_n \neq 0$.

For case *1* the simulation results indicate that with the DAA channel number increasing the impact of the ADC clock period instability on the measurement accuracy of angular coordinates weakens. Hence, for the statistic of 100 realizations, where the signal amplitude $a = 4$, $f_0 = 25$ MHz, $\sigma_{\Delta t} = 1$ ns (2.5% of the period f_0 that corresponds to $\sigma_\xi = 0.157$) and the number of channels $R = 16$ ($F_r^c = 1, F_r^s = 0$), we have received the SD for the generalized angular coordinate estimate $\sigma_x = 0.0251$. The transition to $R = 64$ (with the rest of conditions being the same) yielded lower SD: $\sigma_x = 0.01243$. It was also revealed that the direction finding error caused by the non-synchronous digitizing did not depend on the signal amplitude and cannot be eliminated by its power increase. This fact reiterates the complexity of the problem under discussion.

During the investigations conducted case *2* was used as a reference one since it corresponded to the synchronous cophased DAA. In the process of simulation the main mode was characterized by the non-zero specified values of σ_ξ and σ_n. It should be noted that the dispersions of coordinate x estimates in all three specified cases can be combined into the following additive relationship

$$\sigma_x^2 \Big|_{\substack{\sigma_\xi = c \\ \sigma_n = p}} \approx \sigma_x^2 \Big|_{\substack{\sigma_\xi = 0 \\ \sigma_n = p}} + \sigma_x^2 \Big|_{\substack{\sigma_\xi = c \\ \sigma_n = 0}}$$

that was confirmed during the simulation. The presence of such a relationship enabled us to establish an important-for-practice correlation between the direction finding accuracy degradation owing to $\sigma_\xi \neq 0$ and the rise of σ_x^2 owing to the equivalent increment of σ_n. The investigation of 16- and 64-channel DAA models enables us to argue that in the case of linear arrays the presence of condition $\sigma_\xi \neq 0$ caused by $\sigma_{\Delta t}$ being equal to 5% of the carrier (intermediate) frequency period (the latter is used for digitizing of signals) is equivalent to an almost two-fold reduction of the signal-to-noise ratio in the cophased DAA. The simulation results presented in Table 1 for the case $\sigma_\xi = 0.314$, which corresponds to $\sigma_{\Delta t} = 2$ ns (5% of the period) at $f_0 = 25$ MHz can be considered as comments to the attribute "almost" used in the previous sentence.

Since the power losses of 6 dB in terms of voltage in the engineer practice are close to maximum admissible, it is reasonable to use the 5% value (in the specified sense) of $\sigma_{\Delta t}$ as a boundary level of the possible nonidentity of ADC triggering times over the sheet of DAA.

The solution of problems of measuring the range and frequency selection, unlike the direction finding procedures is less critical to the asynchronous operation mode of ADC. The results of statistical simulation of the range-measurement maximum likelihood procedures indicate that the errors in sampling times that do not exceed the discretization period are not appreciable in practical terms, provided the above procedures use 50 or more ADC samples per pulse duration. By increasing the signal sampling duration we can essentially compensate the ADC clock period instability during the frequency measurements.

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