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A METHOD OF INVESTIGATION OF THE LINEAR DYNAMIC RANGE OF RECEPTION CHANNELS IN A DIGITAL ANTENNA ARRAY

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A method is proposed for determination of the linear dynamic range and of nonidentity of reception channel characteristics of a digital antenna array at the stage of rig trials.

In designing radio-engineering systems with digital antenna arrays (DAA), two parameters of such systems are of primary concern: the instantaneous linear dynamic range (LDR) and the permissible mean-square nonidentity of complex transfer ratios of analog reception channels (by the upper boundary of LDR is meant the point of the transfer characteristic, in which the latter deviates from the straight line by 1 dB or 10%). In rig trials these characteristics should be measured using digital signal processing equipment comprising a part of the reception DAA. We have to use a pilot signal (PS), which is coherent with ADC clock period and comes from a common source simultaneously to all analog inputs of the antenna array in the required range of frequencies. With this approach, the classical single-channel methods of analysis of transient characteristics of reception channels turn out to be inefficient and need some modification.

The purpose of this work is development of a method for investigation of LDR and of the relevant interchannel nonidentity of analog reception channels, adapted for DAA applications and recommended for matching between the DAA analog and digital segments.

The LDR of DAA reception channels can be estimated either directly by ADC samples or by results of their additional gating [1]. The latter may be performed by one of two techniques: without correction and with correction of transfer ratios. A continuous PS is applied to analog channels, through a discrete attenuator with attenuation from 0 to 80 dB and over, changeable with a prescribed increment. The signal amplitude at the generator output is set such that the zero attenuation of the discrete attenuator corresponds to the saturation segment of transfer characteristics of the receivers. This method of variation of receiver input signals makes it possible to work with a fixed power of the noise and of spurious harmonics at the generator output.

Investigation of the reception channel characteristics by the correction-free method is the simplest generalization of the traditional single-channel method of analysis. In the case of DAA, this method permits us to measure the transfer characteristics of all the analog modules and, hence, to obtain full information about absolute values of their nonidentities. As a rule, these data help estimate the actual LDR from below, since the neglected spread of the group time of signal delay, the phase and amplitude nonidentities, and other systematic errors may substantially distort the transfer characteristics.

After turning on the equipment, loading the software, and warm-up, at the first stage of investigations we have to measure the mean square value of the joint noise of the analog and digital reception paths in every channel in the absence of input signals. To do this, the receivers' inputs must be connected to matched loads, while the statistics of the output samples of signals must be formed based on a rather extended set of voltages.

Analysis of statistical characteristics of the noise makes it possible to check another important parameter of the multichannel digital measurer — the ratio between the levels of the mean square deviation and of ADC quantum. For effective coherent accumulation of low-noise signals, the MSD of noise in the analog path has to be no less than one

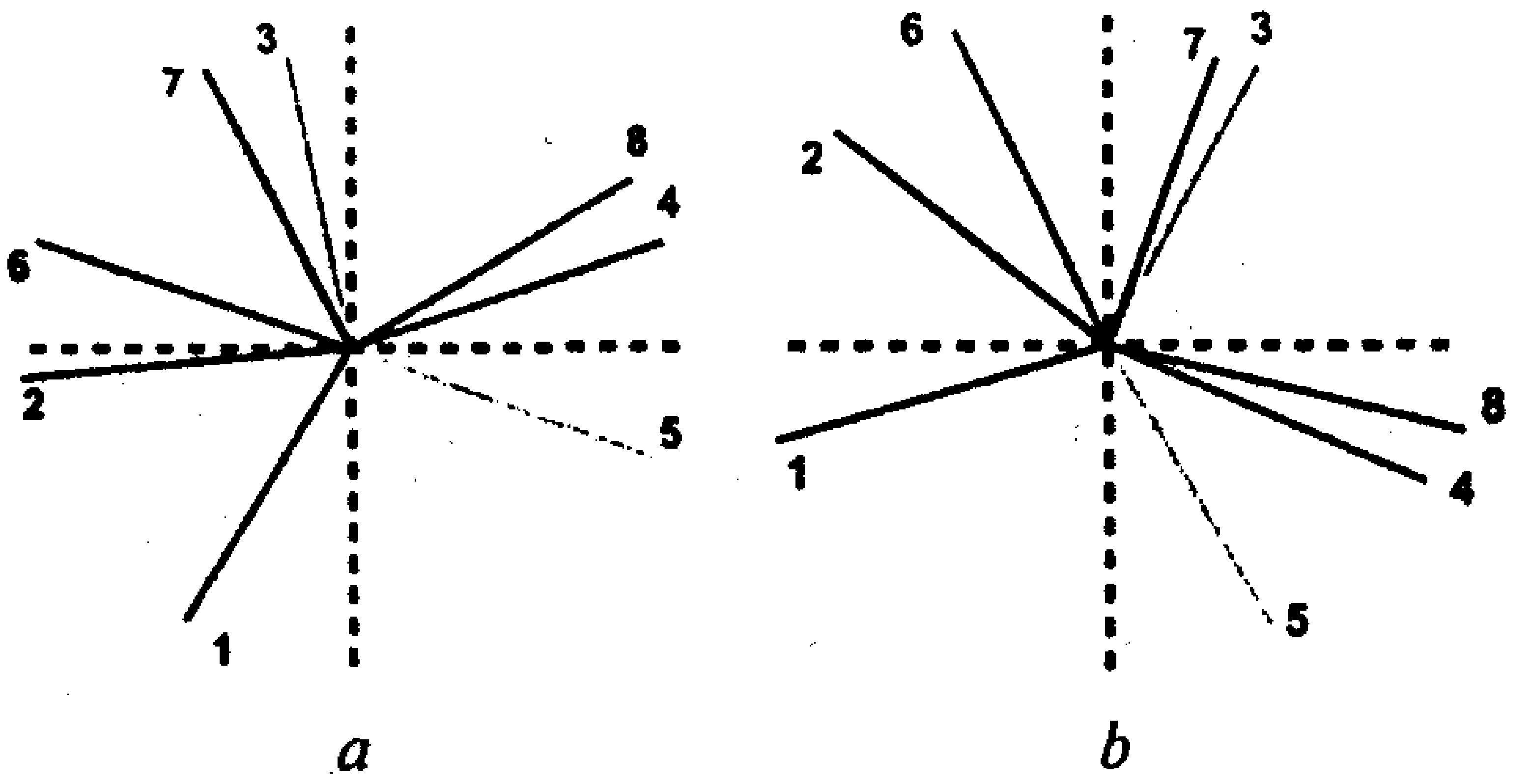

Fig. 1

increment of their digital representation. In the event of additional gating of ADC samples [1], establishment of this relationship will require recalculation of MSD of the resulting noise followed by referring the result, obtained after the additional gating, to the number of digital samples accumulated in the strobe.

After examining the noise characteristics, the inputs of the reception channels under test are connected to the PS-generator output through the attenuator. For each relevant position of the attenuator we must accumulate coherently the voltages at the outputs of the reception channels, and plot the dependence of the modules of resulting voltages on the relative level of the input pilot signal. This level corresponds to the central frequency in the passband of every channel under test. It is desirable to perform the coherent accumulation of signals with the aid of FFT yielding an array of orthogonal frequency filters. With the use of their response to PS, by the maximum likelihood method we can determine the required estimates of the amplitude components of receivers' output signals in the form:

$$a^c = \frac{1}{K^2}\sum_{p=1}^{K} U_p^c \cdot f_p(\omega), \quad a^s = \frac{1}{K^2}\sum_{p=1}^{K} U_p^s \cdot f_p(\omega), \tag{1}$$

where U_p^c and U_p^s are quadrature components of the output voltage of the pth frequency filter synthesized after accomplishment of the K-point FFT, and $f_p(\omega) = \sin 0.5K(\omega - 2\pi p / K) / \sin 0.5(\omega - 2\pi p / K)$ is the amplitude-frequency response of the pth frequency filter.

In Fig. 1 the responses of all channels of the experimental 8-channel DAA are shown as vectors, whose angle of rotation corresponds to the initial phase of the signal at the receiver output while the length — to the voltage absolute value. The difference between attenuation magnitudes of the PS-attenuators for the "*a*" and "*b*" positions was 26 dB, but owing to normalization with respect to the largest response module, this difference does not seem large. This is a good illustration of external manifestation of interchannel nonidentities of receivers' transfer ratios, and of their immunity to variation of input signal levels.

The results obtained in the course of experimental checking of LDR in the absence of correction of the transfer characteristics can be used as initial data for the other method employing preliminary correction of the complex transfer ratios. Since the signal processing mode with correction of channel characteristics dominates in DAA operation, the LDR value measured under these conditions is more suitable to actual functioning of the radio-engineering system.

The correction coefficients, which are necessary for LDR estimation, should be calculated at such a level of attenuation introduced into the pilot signal by the attenuator, when the output voltage of the reception channels corresponds to the upper half of the linear segment of the transfer characteristic. We can find this segment based on the results of the correction-free method of LDR measurement. Selection of the correction point represents a compromise task, since for a more precise calculation of the correction coefficients we have to minimize the impact of intrinsic noise of the receivers, which is achieved automatically at large input signals, i.e., in the upper part of their dynamic range. However, it is in the upper one third of LDR that we have a pronounced discrepancy between transfer characteristics of the channels, and we can see their deviation from a straight line, reaching (according to the LDR definition adopted) 10%. Because of this, the ultimate selection of the transfer characteristic level for calculation of the correction coefficients must be performed by several iterations. As a result, we gradually achieve a maximum of the measured LDR. The point, thus obtained, on transfer characteristics of the channels, permits us to formulate requirements for amplitude of the PS used subsequently for any correction procedures of a particular DAA during its maintenance. Deviation from this nominal value inevitably leads to instrumental loss in the actually attainable LDR, which in turn affects the noise immunity of the whole radio system.

After setting the desirable level of PS attenuation, we proceed to calculation of the correction coefficients. Here the testing generator may be regarded as a source of signal with flat wave front placed on the normal to the antenna array. Obviously, the correction coefficients calculated in this case cannot be applied to angular direction finding of signals, since they take no account of nonidentities of the lines delivering the PS to receivers' inputs. However, for investigation of LDR these assumptions are acceptable.

Provided the PS-source is located on the normal to the antenna array, the required quadrature components of voltages corresponding to receivers' outputs must be identical for all the channels. Thus, the algorithm for calculation of correction coefficients based on a series of *S* digital samples of PS voltages, in the case of a planar row-column antenna array, has the form [2]:

$$\beta^c_{rq} = \frac{\sum_{i=1}^{S} \{U^c_{rq_i} \cdot \hat{a}^c_i + U^s_{rq_i} \cdot \hat{a}^s_i\}}{\sum_{i=1}^{S} \{U^c_{rq_i} + U^s_{rq_i}\}}, \quad \beta^s_{rq} = \frac{\sum_{i=1}^{S} \{U^c_{rq_i} \cdot \hat{a}^s_i - U^s_{rq_i} \cdot \hat{a}^c_i\}}{\sum_{i=1}^{S} \{U^c_{rq_i} + U^s_{rq_i}\}}, \tag{2}$$

where β^c_{rq}, β^s_{rq} are the cosine and sine components of the complex-valued correction coefficient of response of the *rq*th primary channel of DAA, located in the *r*th row of the *q*th column; $a^{c(s)}_{rq_i}$ are the required quadrature components of voltages at the output of the *rq*th reception channel in the *i*th time sample; $U^c_{rq_i}$ and $U^s_{rq_i}$ are the quadrature components of output voltages of the *rq*th channel at the *i*th time instant.

At the stage of LDR investigation the numbering of channels may be arbitrary. During the measurements we may use only a part of the standard set of the channels (for example, immediately after their shipping by the manufacturer). As a result, we may form several groups of receivers, and each group will have its own correction coefficients. Nevertheless, it is desirable to follow a unified numbering, which can be easily put into correspondence with the physical structure of the array and have no alterations at the ultimate hookup.

For the required values of amplitude quadrature components, in calculation of correction coefficients for a flat DAA we may take

$$\hat{a}^c_i = \frac{1}{RQ} \sum_{r=1}^{R} \sum_{q=1}^{Q} U^c_{rq_i}, \quad \hat{a}^s_i = \frac{1}{RQ} \sum_{r=1}^{R} \sum_{q=1}^{Q} U^s_{rq_i}, \tag{3}$$

i.e., the required quadrature components of voltages at the *i*th time instant are formed as a sum of responses of the channels to be analyzed. In the event of continuous numeration, or a linear DAA, we have

$$\hat{a}^c_i = \frac{1}{R} \sum_{r=1}^{R} U^c_{r_i}, \quad \hat{a}^s_i = \frac{1}{R} \sum_{r=1}^{R} U^s_{r_i}. \tag{4}$$

The averaging of voltages over the array channels, as in (3) and (4), permits minimization of the quadrature disbalance for receivers with two quadrature subchannels. However, the operation of summation of quadrature components of primary channel responses, used in (3) and (4) for calculating correction coefficients (2), is acceptable only in the case of small discrepancies between their phase-and-amplitude characteristics. In the case of a substantial spread (Fig. 1) the sums may become zero.

Because of this, in LDR investigations preference is given to correction of amplitude-and-phase characteristics of primary channels related to a real receiver among those present in the array. This particular receiver is considered a standard one (for example, by such criteria as minimum noise factor, faultless operation of the digital circuitry, the largest LDR measured by the correction-free method, minimal disbalance of the quadratures, or in accordance with a prescribed number in the whole list). In this case, the relations for calculation of correction coefficients (of a linear array, for instance) must be supplied with the values of the respective amplitude components $\hat{a}_i^c = U^c_{\text{st}_i}$, $\hat{a}_i^s = U^s_{\text{st}_i}$, where $U^c_{\text{st}_i}$ and $U^s_{\text{st}_i}$ are quadrature components of output voltages of the standard channel at the ith time instant.

Then the values of coefficients β_r^c and β_r^s are calculated, as in (2), by S samples of pilot-signal voltages $U^{c(s)}_{\text{st}_i}$ in the reference channel:

$$\beta_r^c = \frac{\sum_{i=1}^{S} \{U^c_{\text{st}_i} \cdot U^c_{r_i} + U^s_{\text{st}_i} \cdot U^s_{r_i}\}}{\sum_{i=1}^{S} \{U^{c^2}_{r_i} + U^{s^2}_{r_i}\}}, \quad \beta_r^s = \frac{\sum_{i=1}^{S} \left\{U^s_{\text{st}_i} \cdot U^c_{r_i} - U^c_{\text{st}_i} \cdot U^s_{r_i}\right\}}{\sum_{i=1}^{S} \left\{U^{c^2}_{r_i} + U^{s^2}_{r_i}\right\}}.$$

The algorithm of the correction itself, in all the cases considered, reduces to the weighting of voltages of the signal mixture by formulas [2]

$$\tilde{U}^c_{rq_i} = U^c_{rq_i} \cdot \beta^c_{rq} - U^s_{rq_i} \cdot \beta^s_{rq}, \quad \tilde{U}^s_{rq_i} = U^s_{rq_i} \cdot \beta^c_{rq} + U^c_{rq_i} \cdot \beta^s_{rq}, \qquad (5)$$

where $\tilde{U}^c_{rq_i}$ and $\tilde{U}^s_{rq_i}$ are the corrected values of the respective orthogonal components at the ith time instant.

When passing from a flat DAA to a linear one, calculation by (5) becomes simpler, because in the values β^c_{rq}, β^s_{rq}, $U^c_{rq_i}$, $U^s_{rq_i}$ we may merely omit the index "q". In order to improve stability of the calculated correction coefficients to noise impact, for voltages of the standard channel we may use the estimates of amplitude components of its signal (1) obtained at outputs of the array of frequency filters synthesized using the FFT.

The operability and functional possibilities of the method of measurement of LDR with correction of channel characteristics were also checked experimentally. Here we used the above-mentioned set of reception channels of an 8-element DAA. The pilot signal, prior to the interchannel divider, was first applied to a passive attenuator introducing a discrete attenuation into the signal level within the limits from 0 to –70 dB. After preliminary estimation of the LDR length by the correction-free method, the correction coefficients of receiver characteristics were calculated at the attenuation values equal to –40 dB. For any other values we could see a pronounced lowering of the measured LDR.

Based on the corrected samples, the dynamic range was checked by means of repeated introduction into the generator output signal of attenuation with increment 5 dB. The express-estimation of the current results was performed by vector diagrams (Fig. 1). At the point of calculation of coefficients for the ideally corrected channels, all the vectors of channel voltages were "compressed" into a single vector. However, as the signal weakens, the noise fluctuations and nonidentity of the characteristics split this resulting vector into some fan-shaped structure, whose angular dimension increases together with the growth of the attenuation factor of the attenuator in the PS path. The width of divergence of the vector "bundle" of voltage samples can be easily used for visual express-estimation of LDR boundaries and the rate of current nonidentity of the reception channels.

Figures 2–4 display dependencies (obtained with the use of the correction procedure) of mean values of the output voltage modules of the receivers on the normalized levels of the input signal.

Figure 2 illustrates general dependencies of the output signal modules of analog-to-digital receivers on the relative PS level in a rather wide range of the output signal amplitude variations. On the so-called transfer characteristics we can see a linear segment, which is common for all the channels, and segments of the analog modules with different "saturation" levels. The dependencies may have some other shape, since in the experiment there was a 2-3-fold mismatch between the working ranges of the analog and digital paths resulting in a loss of 1 to 1.5 digits, which was a rather good index for the experimental prototype. However, this result gives no way of realizing in full measure the potentialities of digital signal processing. Because of this, for a better matching of dynamic ranges of the analog and digital paths, we have to raise the boundary of the saturation segment or decrease the ADC reference voltage, and allocate not a single quantum of ADC but 2 or more quanta for the noise MSD.

Figure 3 shows in detail a fragment of transient characteristics. The upper LDR boundary in the example under consideration corresponds to the reception path output voltage occupying about 91000 quanta. By subtracting the

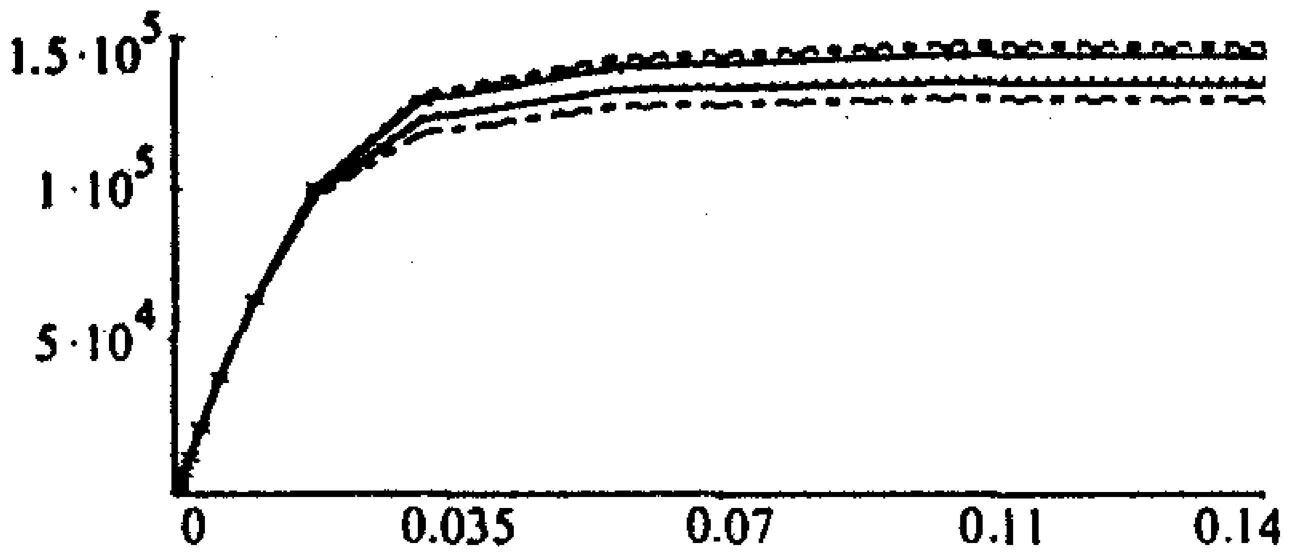

Fig. 2

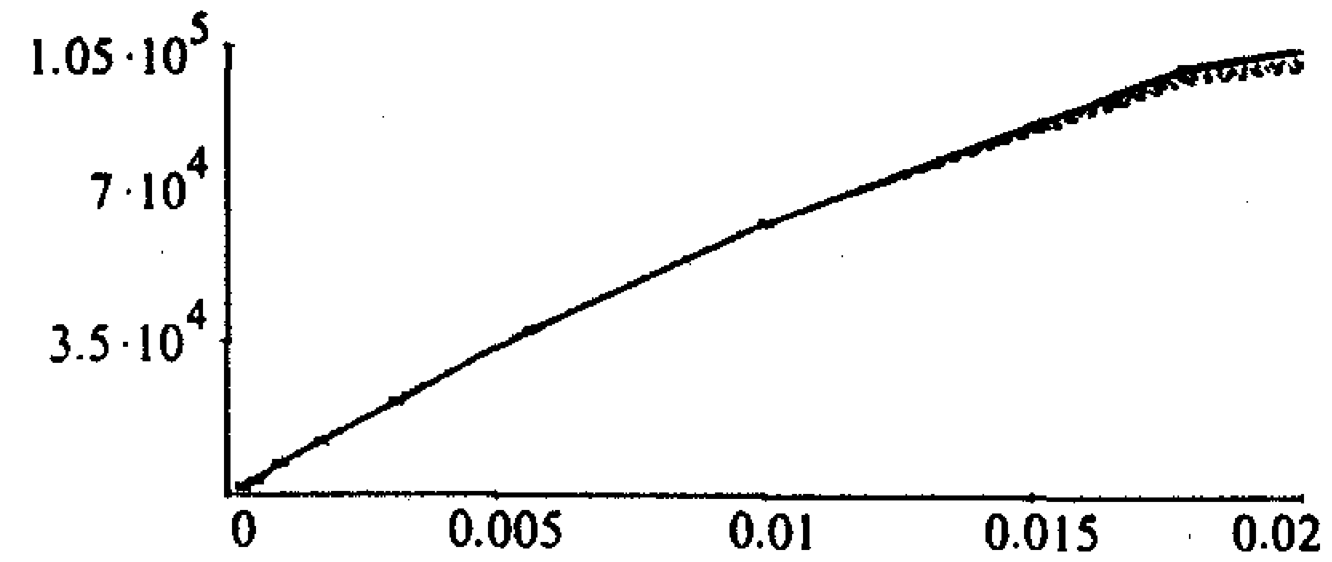

Fig. 3

increment of the dynamic range due to coherent accumulation of signals using the FFT, we see that the overall dynamic range of the analog path, with respect to the unit level, is about 57–58 dB. This agrees well with the acceptance protocol of analog modules used in the experiment. In the course of analysis, in each channel we managed to examine only linear segments of the transfer characteristic with lengths of 33 to 38 dB, since in the case of weak signals the spurious interference of the test generator had a pronounced effect, and we had no attenuator with attenuation factor beyond 70 dB.

Together with estimation of LDR length, the method under consideration permits us to establish the range of variation of input signal amplitudes allowing for operability of the correction procedure. It also makes it possible to visualize the rate of nonidentity of the amplitude and phase characteristics of the reception modules at the central frequency of their passband. In Fig. 4, for different values of attenuation introduced into PS, we can see the graphs of the averaged (over all the channels) ratio between MSD of estimates of output voltage modules of the channels and the measured values of the modules (solid line). The dotted line with markers in the same picture corresponds to the averaged (over the channels) MSD of the measured initial phase of the output signals.

Just in the same manner, in Fig. 5 we can see the dependencies of MSD of the modules of output voltages of a pair of reception channels (the upper curves), and the averaged level of MSD of their intrinsic noise (the straight dotted line with markers) obtained after an additional gating of ADC samples [1]. The abscissas in Figs. 4 and 5 show the relative magnitude of the input signal.

In the overwhelming part of the examined dynamic range of the receivers (with length close to 35 dB), MSD of the measured initial phase never exceeded 1°, and within the introduced attenuation from –10 to –60 dB it was less than 1.6°. As for interchannel discrepancies in amplitude, in the same range of introduced attenuation from –10 to –60 dB, the value of the MSD averaged over channels, of output voltages (with MSD normed to the modules) turned out to be below 4.5%. For such interchannel discrepancies we can predict an insignificant "bloating of zeroes" in the radiation pattern synthesized by the digital technique. We can also expect a possibility of obtaining a depth of suppression of active clutter, limited by the LDR area, at a level of 30–40 dB. It is not inconceivable that the measured MSD of the estimates of initial phase and of spread of amplitude responses need some correction taking into account the rather intensive noise in the output signal of the PS generator. In the absence of an attenuator, this noise may exceed the MSD of intrinsic noise of reception channels by about 19 dB. In the central and lower fragments of Fig. 5 we can clearly see that the MSD of estimates of modules of the output signal in the channels, arising from the generator noise, repeats the transfer characteristic of the respective receivers almost completely, but on a different scale.

Similarly to the results of the method without correction, the graphs obtained with regard to correction, make it possible to judge the value of nonidentities of the amplitude and phase responses of the receivers. The dependencies measured by both methods are similar in a qualitative sense, but differ in their scale. The use of correction (Figs. 4 and 5) permitted substantial smoothing of these nonidentities due to their determinate nature. Because of this, the method of measurement of receiver parameters with correction of their characteristics can be recommended as preferable — for acceptance and in tests of any systems with DAA.

A further generalization may be application, as a testing excitation, not only of the noise signal, but of a multifrequency packet of harmonic signals. The difference in frequencies of these signals may be set not only with regard to coverage of the relevant spectral band, but in such a manner that (as in communication systems with OFDM-modulation) after completion of the FFT operation the signal responses could fall at the maximums of frequency responses of different

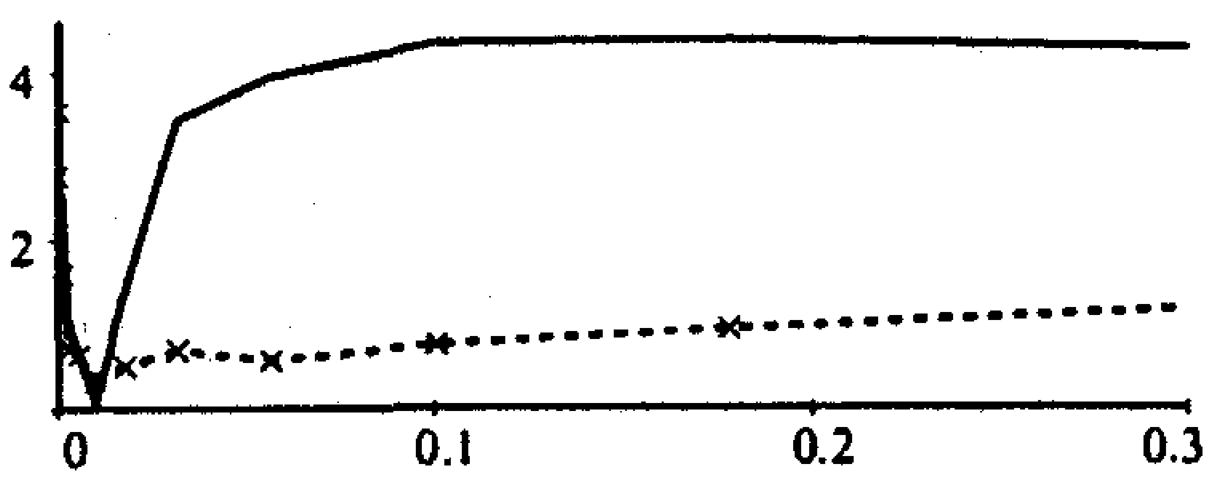

Fig. 4

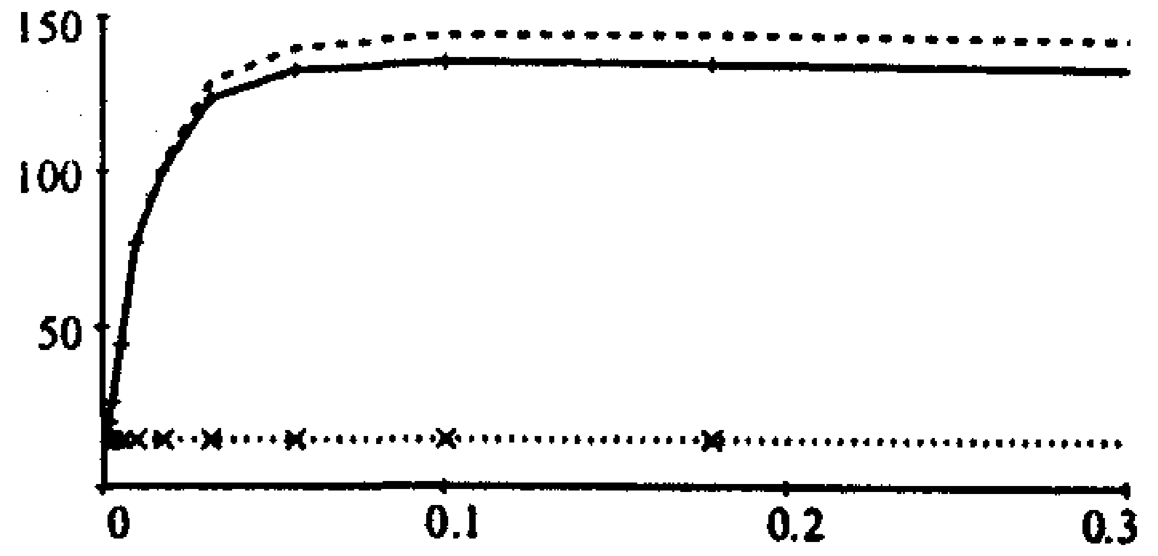

Fig. 5

FFT-filters and become orthogonal. Evolution of levels of signal amplitudes at the outputs of FFT-filters, in the case of PS attenuation variations, will make it possible to watch the LDR change in a rather wide spectral band. As distinct from the noisy PS, application of the multifrequency packet does not require any special modifications of the measurement method under consideration. Moreover, calculation of the correction coefficients can be performed easily based on the responses of the frequency filters, when we substitute, instead of the required amplitude values, the sum of voltages of signals with different frequencies. Another variant consists in calculating the correction coefficients separately for every tonal signal used in the measurements. After that we average the calculated values of the coefficients for every channel over the available set of frequencies.

When the distribution of signals about the array of the frequency filters is nonorthogonal, calculation of the quadrature components of amplitudes in R channels may be performed based on a well-known matrix relationship

$$A = \{F^* F\}^{-1} F^* U \qquad (6)$$

where U is the matrix with entries $\dot{U}_{ir}$, $i = 1, 2,..., K$; $r = 1, 2,..., R$, and the matrix is composed of K discrete samples of complex voltages of the signal mixture of R channels including the K-point FFT and correction; F is the matrix of amplitude-frequency responses of K frequency filters synthesized by FFT, and this matrix has elements $f_i(\omega_m)$, $m = 1, 2,... M$, identical to those contained in (1); M is the number of signals in the testing packet; p is the number of the frequency filter; ω_m is the radial frequency of the mth signal; and A is the matrix whose elements a_{mr} are unknown complex amplitudes of M signals in R reception channels.

The value of (6) obtained with the aid of the least squares method makes it possible to calculate the optimal estimates of the quadrature components of amplitudes which, as before, will form a basis for plotting the relevant characteristics of the reception channels. In a similar manner, relation (6) can be used for estimating the amplitudes in the case of orthogonal arrangement of signals in frequency.

Thus, the main feature of the presented method of investigation of LDR of DAA reception channels consists in correction of their amplitude and phase characteristics. The experimental results have confirmed the effectiveness of this approach, which may be adopted as a proposed standard for the respective trials and certification.

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