

# High Resolution Noise Radar without Fast ADC

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**Abstract**—Conventional digital signal processing scheme in noise radars has certain limitations related to combination of high resolution and high dynamic range. The bandwidth of radar signal defines range resolution of any radar: the wider the spectrum the better the resolution. In noise radar with conventional processing the sounding and reference signals are to be digitized at intermediate frequency band and to be processed digitally. The power spectrum bandwidth of noise signal which can be digitized with ADC depends on its sampling rate. In currently available ADCs the faster is sampling rate the smaller is its depth (number of bits). Depth of the ADC determines relation between the smallest and highest observable signals and thus limits its dynamic range. Actually this is the main bottleneck of high resolution Noise Radars: conventional processing does not enable getting high range resolution and high dynamic range at the same time. In the paper we discuss ways to go around this drawback by changing signal processing ideology in noise radar. We present results of our consideration and design of two types of high resolution Noise Radar which uses slow ADCs: noise radar with digital generation of sounding signal and analog evaluation of cross-correlation and stepped frequency noise radar. We describe main ideas of these radar schemes and results of experimental tests of the approaches.

**Keywords**—noise waveform, stepped frequency, stepped delay.

## I. INTRODUCTION

**R**ANGE resolution and dynamic range are the most important performances of radar systems. Both of them describe how good radar in target detection and its localization is. High range resolution gives possibility to distinguish two targets at closer distances, whereas high dynamic range enables to detect target with low reflectivity at the background of a strong target response. There are many radar applications which need high both resolution and dynamic range, such as long range radars, through-the-wall and ground penetrating radars. Operation of most of radars is based upon correlation processing of radar returns which enables ranging and matched filtration. Especially this is valid for noise radar where the sounding signal is random. A copy of the transmitted signal is to be delayed and used as a reference for that. Conventionally, digital processing is used for estimation of the cross-correlation in the following way: the reference signal and radar returns are sampled at the IF band using an appropriate ADC and processed in a computing device like PC or digital signal processor. Using of noise signal in this approach enables to get such benefits as high interference immunity and high electromagnetic compatibility, low probability of interception to the radar. But the dynamic range of such system is limited by the

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depth (number of bits) of the ADC used whereas bandwidth of the sounding signal must be limited by its sampling rate. Lack of ADCs with both high depth and sampling rate leads to difficulties in design of high performance radars using this approach. The aim of the investigation presented in the paper is to describe approaches which can provide as high as possible both bandwidth and dynamic range of the noise radar. These approaches enable using slow ADCs for high resolution noise radars

## II. CORRELATION ESTIMATION IN RADAR APPLICATIONS

Correlation estimation is the heart of many types of radar, especially those which use random or chaotic signals. This procedure includes delaying of signals with respect to each other, multiplication and integration. This can be implemented in analog way, but lack of effective analog variable delay lines makes range scanning too difficult to realize. Recent progress in development of digital circuits enables using ADCs to digitize radar signal at intermediate frequency band and to perform delaying, multiplication and integration in digital way. Scheme of such radar is shown in Fig. 1. In conventional noise radar [1-4], the reference signal is normally sampled with the help of an appropriate ADC at the intermediate frequency band which enables further signal processing in digital way. Delaying is implemented digitally via proper selection of the sampled data which is permanently updated in RAM memory. Correlation processing is usually done in spectral domain using FFT procedures [1-4].

Maximal bandwidth of the signal which can be digitized is equal to a half of the sampling frequency of the ADC. Currently available high speed ADCs can provide sampling frequencies up to several GHz which gives range resolution about tenths of cm. But they have dynamic range of about 40 dB due to low resolution in signal level (8 bits) [3, 4]. At the same time the multi-bits ADCs with high dynamic are normally rather slow (24 bit ADCs providing dynamic range more than 100 dB are available with sampling frequencies of several MHz only). Besides, online processing of wideband signals using this scheme is a challenge because rather high data flow is to be processed.

## III. STEPPED-DELAY METHOD FOR HIGH DYNAMIC RANGE NOISE RADAR

We present an approach to estimation of the radar cross-correlation which uses combination of digital and analog processing of wideband noise signals. This procedure includes delaying of the transmitted signals with respect to the sampled reference with the help of digital signal generators, analog multiplication and integration. The design of such radar is

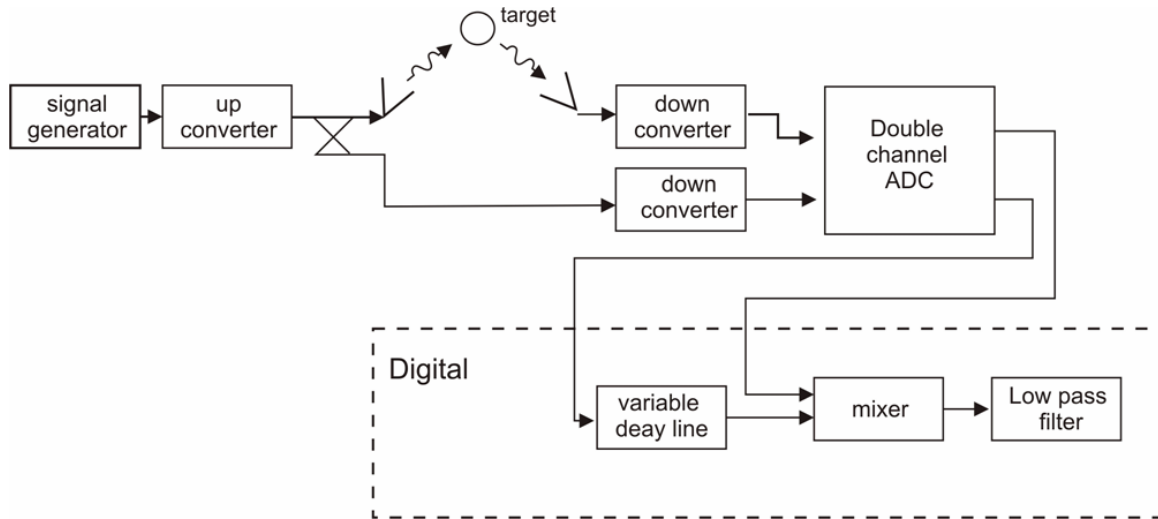


Fig. 1. Diagram of noise radar with digital signal processing.

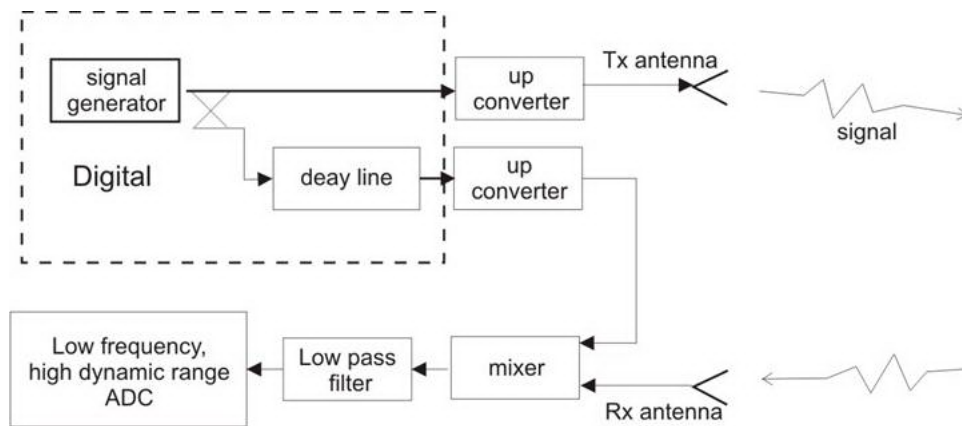


Fig. 2. Diagram of noise radar with digital generation and analog processing of signals, and slow ADC sampling of Cross-correlation giving range profile.

based upon analog processing of wideband signals and digitizing of the results at relatively low frequency (Fig. 2).

We have carried out experimental testing of the stepped-delay method using propagation of noise sounding signal through a cable rather than its propagation in the open space. The data have been generated in a PC for both sounding and reference signal which have been uploaded into the corresponding channels of the arbitrary waveform generator AWG-472 (EUVIS, Ltd) [5]. In this way, AWG-472 continuously generates both sounding noise signal and its delayed copies. The reference signal was composed as a series of transmitted signal copies with the required delays and numbers of range bins. The signals have not been up converted since AWG-472 clock frequency enabled direct generation of such signals. Both signals have the maximal duration of 2 ms which is a limit for the AWG-472 at the 2GHz clock frequency. In the experiment, the reference signal contained 20 copies of the transmitted signals with the delays which formed 20 range bins having 4 ns gaps between each of them. The 4 ns delay corresponds to 80 cm length in the cable versus 120 cm length in air, since the dielectric constant of the cable material equals 2.2. Duration of the signal for the each delay was

0.1 ms, which defined the value of integration time at each range bin. Overall duration of the measurement cycle was 2ms. Spectrum bandwidth in this experiment was limited not by AWG-472 device, but by the available mixer having bandwidth of 190MHz.

Figure 3 shows a block diagram of the two target simulation experiment. Two targets at different ranges were modeled by two cables with different lengths connected in parallel. Difference in lengths of cables was 6 m.

Figure 4 shows the range profile obtained with the help of stepped-delay mode. AWG signals and, consequently, range profiles are repeated with 2 ms period. The 4ns delays in the signal enabled real-time integration in the mixer +amplifier +LPF, while further sampling with a slow ADC enabled range scan within 016 m (in cable). It is seen from the range profile obtained a good agreement between real and measured range differences of 6 m.

Besides, we carried out experiments with higher signal bandwidth: AWG generated sounding noise signal with 500 MHz bandwidth and corresponding reference signal generated by shifts of parts of the sounding signal for corresponding delays. There were 100 range bins with temporal step of 0.25

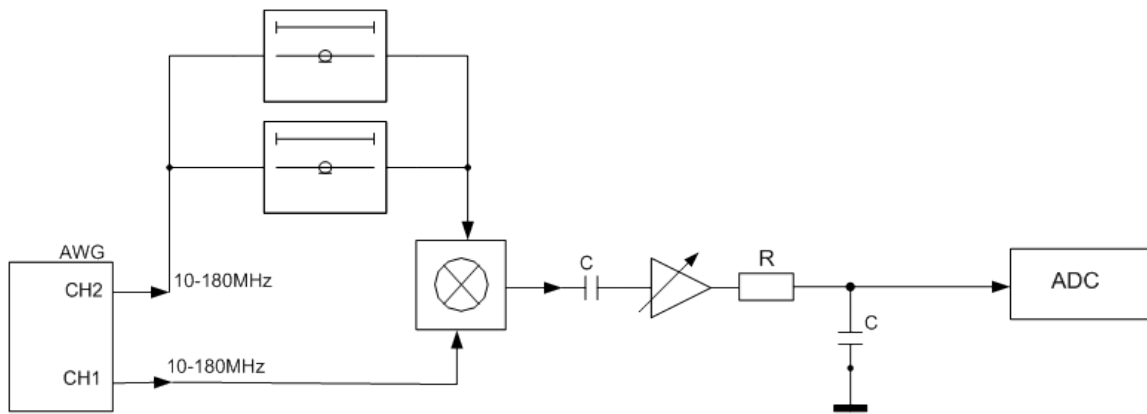


Fig. 3. Block-diagram of the setup for testing of the stepped-delay method for range measurement: two targets case.

ns. Duration of signal corresponding to each range bin was 0.02s. The experiment diagram was the same as depicted in figure 3. The two target scene is simulated by propagation of signals in two cables with lengths of 2 m and 2.4 m. Difference between cables corresponds to 60 cm one-way propagation in free space or 2 ns. The obtained range profile (Fig. 5) enables detection of two peaks. Therefore, the experimental testing carried out has shown that the approach is valid for estimation of cross-correlation in radar applications.

IV. STEPPED FREQUENCY NOISE RADAR

Various radio location tasks need the radar to be sensitive to presence of objects in certain limited area and to be not sensitive to their presence outside of this area. Normally, azimuth and elevation angle sizes of this area are limited by the antenna pattern. Size of the area along range is usually specified by limitation of radiated signal power. Main drawback of this approach is strong dependence of zone dimensions on radar cross-section of the target. This dependence can be decreased by using coherency of the oscillations radiated

by detector antenna. For partially coherent waves [6] effects of interference are present but have lower order than for the monochromatic waves. The coherence length of these oscillations is inverse proportional to their bandwidth. At the range exceeding the coherence length interference does not occur. Coherence function of wave field is determined by the shape of the signal spectrum. Increase of the bandwidth leads to decrease in coherence length. Oscillations generated by noise sources [7, 8] are also reckoned partially coherent. These signals are successively used for sounding in radars [1-4, 9, 10]. This can significantly reduce the dependence of the size of the zone size from the radar cross-section.

This method solves the problem of detection within a given area, but the problem of resolving the targets in range and range measurement remains unresolved. This disadvantage can be eliminated by using for sounding short pulse signals or complex signals with the required bandwidth, for example, stepped frequency [11] or frequency hopping [12] variation of carrier frequency or signals with frequency modulated by chaotic or noise signal [13]. Then, within a given area it becomes possible to resolve targets in the range and to estimate

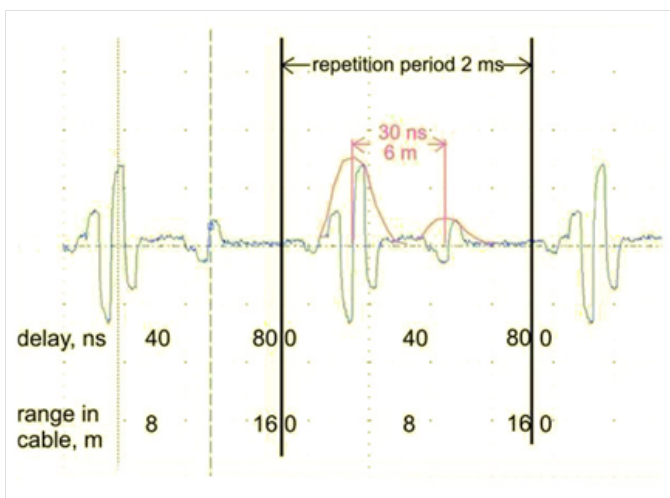


Fig. 4. Cross-correlation between transmitted signal and the reference, which gives the range profile, obtained with the help of stepped-delay method and AWG-472: two targets case.

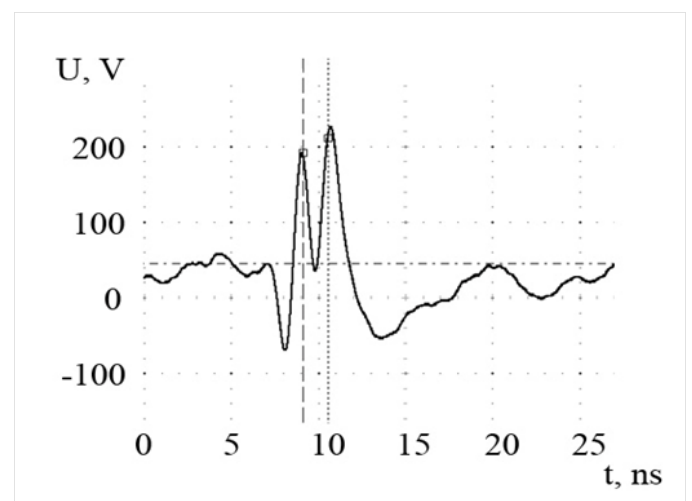


Fig. 5. Range profile in case of two targets obtained using stepped-delay radar with 500 MHz noise signal bandwidth.

their ranges. However, sidelobes of a reflector outside the specified zone can produce certain interference. Particularly high level of interference may be produced by objects outside the zone having high radar cross-section. The pulse signals with given bandwidth have the same resolution as continuous noise signals. But, unlike them, pulse signals do not have range sidelobes and, consequently, the response of side object does not produce interference to the given zone. However, devices forming ultra short pulses have limitations for the peak and, consequently, average power, which can significantly limit the working range of the radar. We develop and test experimentally a method for localization of a given area in range and for measuring distances to objects and for resolving targets within this zone without adding restrictions on the radar working range. To solve these problems we propose radar with a continuous transmitted signal composed of adjacent noise pulses (steps). The carrier frequency can be changed arbitrary from step to step. Scheme of synthesized spectrum of conventional stepped frequency radar is shown in Fig. 6. Illustration of spectra of frequency steps and synthesized spectrum of noise stepped frequency are shown in Fig. 7. It has to be noted that synthesized spectrum for the noise stepped frequency signal is continuous. This corresponds to a non-periodic autocorrelation function of this signal. This proves that radar with such sounding signal will be free of ghosts in range. The order of radiation of frequencies can be chosen arbitrary. For example, it can be varied randomly or linearly. Below, we describe design of the radar, its main parameters and present results of its laboratory tests.

#### A. Experimental Prototype of Noise Stepped Frequency Radar

We have developed and designed a noise radar prototype including transmit and receive antennas, transmitter, receiver, control unit and processing unit. Simplified block diagram of this radar microwave part is shown in Fig. 8. Noise signal is generated by synthesizer, amplified by power amplifier and radiated by the transmitting antenna. The transmitted signal is continuous sequence of narrowband noise signals with

carrier frequency variation with a constant step on a discrete mesh of equidistant frequencies. The bandwidth of the noise signal at each point is such that it is coherent to signal reflected by targets within the working area of the radar. Part of the probing signal is coupled and fed to the input of reference channel of receiver. Radar returns are fed to the second channel of the receiver. In-phase and quadrature components are extracted in the receiver in the region of zero-beating using quadrature detector. They are amplified, filtered and fed to processing unit to a dual-channel ADC. Sampled signal is stored in a memory device, processed using signal processor and displayed. The processing consists in integration of received signals for frequency steps so that one sample is formed from each step. These steps form a discrete spectrum of multiplied signals. In order to obtain range profile one needs only to perform discrete Fourier transform of this spectrum. Maximum probing signal power can reach 600 mW and can be regulated by an attenuator. Power of the reference signal is 28 mW. Range resolution in free space equals to 0.31 m.

Frequency mesh is formed using a synthesizer with reference frequency of 999.5 MHz. For this purpose a device using method of direct digital synthesis (DDS) is used. The output signal of the frequency synthesizer can be tuned in the frequency range 130...380 MHz. The minimal time step of adjustment is 1 ms, the maximal is 8 000 ms. The minimal frequency step is 1 MHz. The order of frequency switching is determined by the combinations of control digital codes, which are prepared in advance and stored in memory of control unit. In order to receive the random signals a voltage controlled oscillator is frequency modulated by noise source signal. The source of the noise is p-n junction of a transistor having normal distribution of amplitudes and "rectangular" spectrum in the frequency range 0.1...14 MHz at -3 dB level. To ensure high stability of the signal spectral characteristics the noise generator based on voltage controlled oscillator has an automatic gain control system. The voltage controlled oscillator is controlled by a phase locked loop with a time constant of 5 ms. The voltage controlled oscillator signal

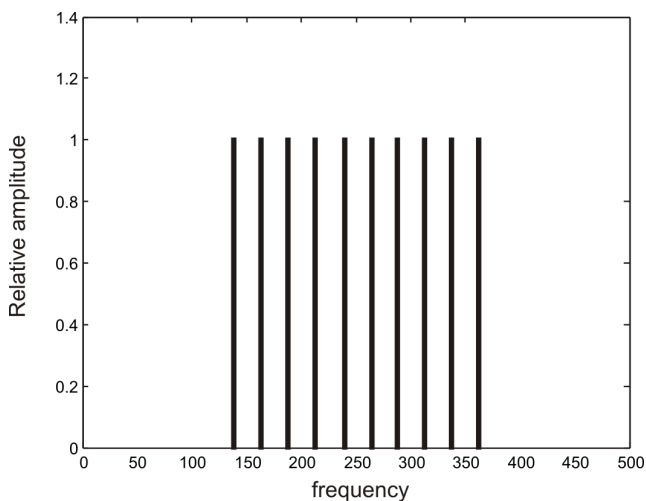


Fig. 6. Scheme of synthesized spectrum of stepped frequency radar.

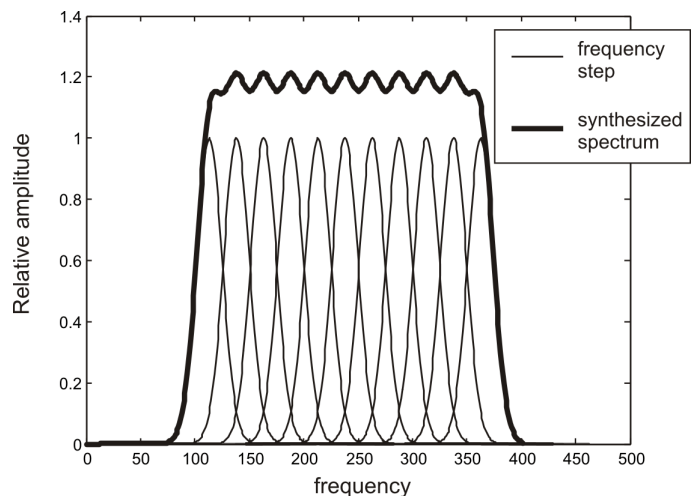


Fig. 7. Illustration of how spectrum of each frequency step and synthesized spectrum are formed in stepped frequency noise radar.

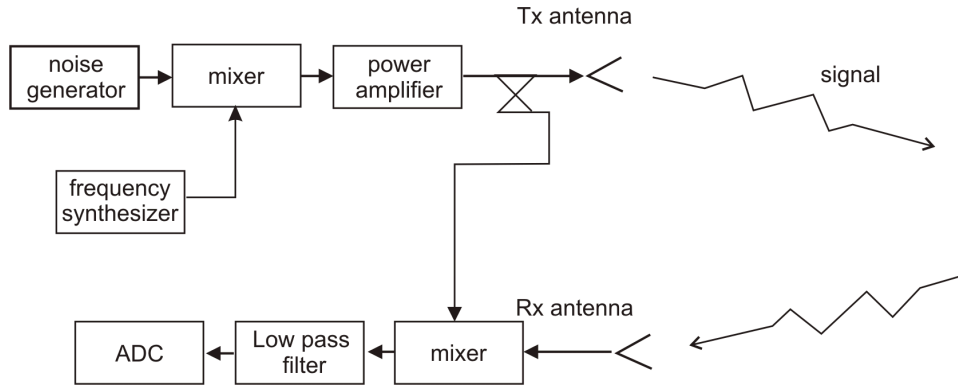


Fig. 8. Cross-correlation between transmitted signal and the reference, which gives the range profile, obtained with the help of stepped-delay method and AWG-472: two targets case.

bandwidth can be smoothly varied from 1.8 to 100 MHz by adjusting threshold of the automatic gain control. Carrier frequency of the probe signal can be adjusted from step to step in the range 950...1 430 MHz with a minimal frequency step of 1 MHz. The duration of the transition process in a discrete adjustment of the carrier frequency is 0.1 ms. Alternatively, stepped frequency noise signal can be generated in the described above arbitrary waveform generator. In this case, a set of narrowband noise signals with varied central frequency is recorded to the device.

Dynamic range of wideband UHF receiver is higher than 110 dB. Receiver noise figure is 4.5 dB, the unevenness of amplitude-frequency characteristics is lower than 1 dB, bandwidth of the quadrature low pass filter is 5 MHz. Spectrum of the output signal of the radar receiver is located in the low frequencies. This allows using low-cost ADC with a relatively low throughput (clock rate of 0.044...10 MHz) and large (over 100 dB) dynamic range. Obtained range profiles of the noise signal show range selectivity of the noise stepped frequency radar at each central frequency step. Obtained range profiles of a scene containing scatterers at two different distances using synthesized spectrum of 500 MHz band show that at absence of frequency modulation the levels of signals reflected by the target at 2.2 m and by passive interference at 7.8 m are nearly equal. If bandwidth of FM signal is about 30 MHz then signal from the interference at 7.8 m is substantially weakened. If bandwidth is 54 MHz this response is suppressed almost completely. At the same time, the response from target at 2.2 m range decreases with the coefficient of 0.87 and 0.63, respectively. This shows that noise stepped radar enables elimination of responses at certain high distances preserving sensitivity and resolution at closer ones.

It should be noted that the signal from the passive interference is observed in the signal channel of receiver. It is weakened in the second mixer, which performs multiplication of reflected and reference signals in the developed coherent receiver. Therefore, control of the position of localized zone in range can be done in reference channel at input frequency or the first IF frequency. Analysis of the obtained range profiles shows that the presence of frequency modulation at each step significantly reduces the influence of response from passive interference on the results of the evaluations in the

area bounded by an interval of coherence, in comparison with the results that can be obtained for the non-modulated stepped frequency signal. This fact may be used, for example, in ground penetration radar for tuning off from the interface air-ground by choosing delay in reference channel so that its response is outside the coherence interval. Besides, such radar will be rather robust against electromagnetic interference because interference will not be coherent to the reference signal.

## V. CONCLUSIONS

In the paper, we have presented two approaches for obtaining range profiles in noise radars which enable obtaining both high dynamic range and high range resolution. It has been shown that bottleneck of conventional noise radar processor is the ADC because currently available ADCs do not have high sampling rate and high dynamic range in the same device. One of the proposed approaches is based upon generation of sounding signal and its delayed copy in arbitrary waveform generator. The correlation is estimated using analog mixing and low pass filtering of high frequency radar return and high frequency reference signal. The resulting signal is digitized by a comparatively slow ADC. Variation of delay between sounding and reference channels is to be done by digital delay of generated in arbitrary waveform generator signals. We presented results of experiments aimed at obtaining range profiles using this approach. We demonstrated possibility of obtaining high resolution. Digital scheme for noise signal generation enables controlling of sounding signal spectrum shape.

The second approach is based upon stepped frequency radar concept but with narrowband frequency modulation of the sounding wave. This enables combination of benefits from both stepped frequency and noise radar concepts such as low bandwidth of the signal at the output of the radar mixers and high electromagnetic compatibility, high interference immunity. We have carried out experimental tests of this approach. Behaviour of synthesized noise signal phase has been studied in case of stepped frequency. Besides, we have investigated the basic radar performance such as: spectral characteristics of probing signal, switching time of its central frequency, output signal of quadrature detector, range profile, etc. Possibility of

range limitation is experimentally shown in the observation area jointly with selection and measuring of the target distance within this area when using sounding noise signals with the synthesized spectrum. This can substantially reduce the interference level during detection, tracking and measuring target coordinates. Both approaches do not require high speed ADCs which enables to use high depth and high dynamic range ones.

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