PAPER • OPEN ACCESS

Mathematical and hardware modelling of MST radar signals

View the article online for updates and enhancements.
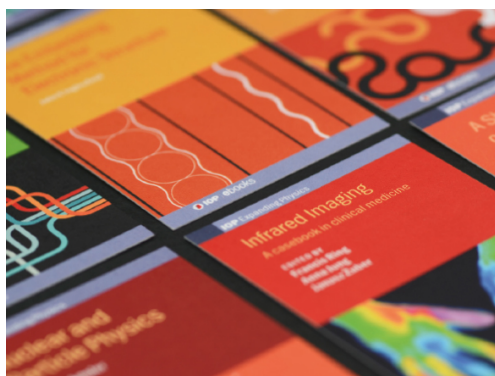
Mathematical and hardware modelling of MST radar signals

D D Dmitriev, V N Ratuschnyak, A B Gladyshev, M A Golubyatnikov and M E Buravleva

Siberian Federal University, 79 Svobodny pr., 660041, Krasnoyarsk, Russia

E-mail: dmitriev121074@mail.ru

Abstract. The study examines the features of formation of radar signals, their structure, and software and hardware complex of MST radar. The results of formation of radar pulses with different types of phase and amplitude-phase modulation, as well as the results of generation of these pulses and their spectral analysis are presented. These results are obtained by using hardware based on PXI modules produced by National Instruments and Keysight and a software model created in the LabVIEW development environment.

1. Introduction
The analysis of the state of the atmosphere is the most important task in the field of meteorology. Information on wind speed and direction at different heights, magnitude of turbulence and atmospheric tide is necessary for ensuring aviation safety, and the accident-free movement of land and sea vehicles. Currently, a network of meteorological stations is used to obtain information on the dynamics of atmospheric phenomena. These stations determine standard meteorological indicators on the surface of the Earth. MST radars are based on Fresnel and Bragg scattering from turbulent formations and on reflection of electromagnetic waves in various layers of the atmosphere. The temporal position of the reflected signal and the frequency shift due to Doppler effect provide accurate information about the height and speed of movement of atmospheric inhomogeneities. MST radars are used at objects with special environmental monitoring zones. In such zones, there is a need for a comprehensive study of the parameters of the neutral atmosphere up to heights of 100 km, the three-dimensional velocity vector of turbulence, mesospheric "silvery" clouds, and the electron concentration of the ionosphere. Such objects include airports, seaports, scientific observatories.

The complex task of choosing the frequency-code structure of radar signals and building the structure of the antenna system arises in the development of MST radars. An important part of the development of the MST radar is the choice of a signal processing method with a low signal-to-noise ratio. Therefore, to compensate the side lobes of the autocorrelation function, special sensing and complex noise-like signals, as well as signal components with different modulation laws are used [1-3].

2. Software implementation of MST radar signals
The advantages of developing compact MST radars with a phased array of small elements are their low cost, low energy consumption, and high mobility. The disadvantage of their development is the problem of small energy potential. This problem is a consequence of a general decrease in the signal-to-noise ratio at the receiver input. It arises from a decrease in the aperture of the antenna and a decrease in the number of transmitting modules. This does not allow using standard algorithms for suppressing reflections from local objects and highlighting useful signals against their background. In

such conditions, the most promising methods will be adaptive compensation of interfering signals using autocompensators or compilation of a "map of local objects" [4, 5].

One of the most promising approaches to the problem of improving the resolution of the MST radar while reducing their size is the use of multi-frequency signals. In this case, the signal with a lower frequency serves to eliminate the side interference maxima of the radiation pattern and to resolve the phase ambiguity of the signal at a higher frequency. The main problems of this approach are to ensure the coherence of signals and to ensure the identity of the high-frequency path at different frequencies. The formation of multi-frequency signals using the frequency and time standard as a reference generator provides signal coherence. The application of the developed microwave elements with high-precision path calibration and improved phase-frequency and group delay time characteristics ensure the identity of the high-frequency path at different frequencies. Thus, the use of these approaches will allow implementing flexible control of the directional diagram and working both in the mode of spatially spaced antennas and in the mode of the Doppler swinging beam.

The following requirements for the functionality of the MST radar should be considered to solve the problems of vertical sensing of the atmosphere and generating signals by a radio transmitting device together with a low-element phased antenna array:

1. Ensuring the formation of a grid of operating frequencies in the range of 40–60 MHz in 20 kHz increments.

2. Ensuring the generation of various radio pulses with a duration from 1 to 50 microseconds at the output of the master generator; the follow-up period is from 20 to 60 microseconds:

- rectangular single pulse;
- single pulse with Gaussian envelope shape;
- a single pulse with a modified Gaussian shape of the envelope;
- pulses package in the form of an additional code;
- pulses package in the form of the Barker, Gold code, etc.

3. The power amplifier must provide undistorted amplification of radio pulses coming from the exciter output.

4. The output power in the pulse must be not less than 1 kW, the average power must be determined by the parameters of the radio pulses at the input.

5. The standing wave factor at the output of the power amplifier must be less than 2,5.

6. Providing the possibility of phase delays in each channel of the low-element grid for electronic scanning of the atmosphere.

To date, master vector generators of signals are mainly used for the formation of radar signals with a certain type of modulation. For these generators the modulating sequence is formed by reading from memory or in real time. The process of forming a radar signal consists in creating quadrature components, the law of change in time of which corresponds to a given type of modulation.

The principle of generating of sensing signals is as follows. The FPGA generates a digital code for the common-mode $I(t)$ and quadrature $Q(t)$ components of the sensing signal. This code is generated according to the algorithm assigned in the special SubVi LabVIEW software module, which provides maximum flexibility in generating the specified signals during programming. The digital code of the generated signal is translated into an analog signal by a digital-to-analog converter (DAC). The common-mode and quadrature components of the analog signal from the DAC output are filtered by a low-pass filter (LPF) and passed to the input of an arbitrary waveform generator. The vector signal generator uses direct transfer of signals from the main band to the radio frequency range. Its inputs receive the common-mode and quadrature components of the modulating sequence of the pulse signal and a continuous HF signal at the carrier frequency from the high-frequency generator. Then, the generated HF pulse signal goes from the output to the power amplifier.

The basis for forming the digital code of the modulating sequence is the FPGA. Using the CORDIC processor, which is identical in hardware resources to the pipeline processor and operates in

rotation mode, allows getting at once the quadrature components of the pseudo-random sequence of the navigation signal $I(t)$ and $Q(t)$ [6]. The CORDIC processor works according to the equation:

$$x^{(i+1)} = x^{(i)} - d_i y^{(i)} 2^{-i},$$
$$y^{(i+1)} = y^{(i)} + d_i x^{(i)} 2^{-i}, \qquad (1)$$
$$z^{(i+1)} = z^{(i)} - d_i \tan^{-1} 2^{-i},$$

where $x = \cos(z)$, $y = \sin(z)$, z − target angle, $d \in \{-1, 1\}$.

There are several basic FPGA architectures, each of which has an advantage either in terms of speed or ease of implementation. When developing computing architectures that operate at 100–200 MHz frequencies, the pipelining of calculations is necessary. Despite the fact that the pipeline architecture has large overhead costs for equalizing the delays of computing blocks, its use is justified when processing and converting signals for solving radar tasks. To speed up calculations of the rotation angle of the vector generated signal, the intermediate values of tan-12-i are intermediately calculated and stored in registers. At each iteration, the sign of the intermediate angle value is checked, and then the increment of the angle is selected for the next iteration of the pipeline. The pipeline implementation allows calculating the values of $I(t)$ and $Q(t)$ in a single clock cycle, and is able to operate at a frequency of more than 100 MHz.

The flexible software architecture of LabVIEW allows programming the necessary type and modulation of radar signals in the FPGA and automatically compiling the VI LabVIEW code in VHDL to implement the FPGA logic (figures 1, 2).
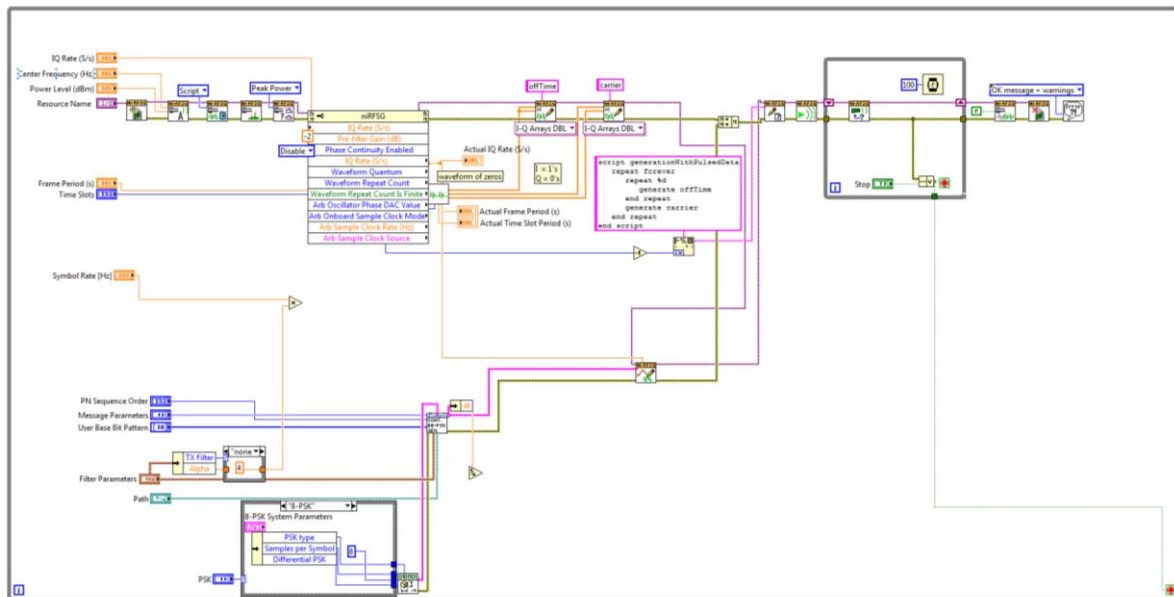

Figure 1. LabVIEW VI block diagram of MST radar signal generation.

At the same time, this software architecture allows changing all parameters of the generated radar signals: pulse duration, frequency, repetition period, modulation type, signal base (figures 3, 4).

3. Software implementation of MST radar signals
To reduce the time and cost of developing a hardware implementation, it is advisable to use a range of modular hardware elements. For example, PXIe modules produced by National Instruments, Keysight such as: vector generators, analyzers, programmable FPGAs, DAC and ADC fully meet the requirements for creating radar signals of a given structure and for their emission in the propagation

environment. They allow flexible controlling signal parameters and overall sensing of various layers of the atmosphere.
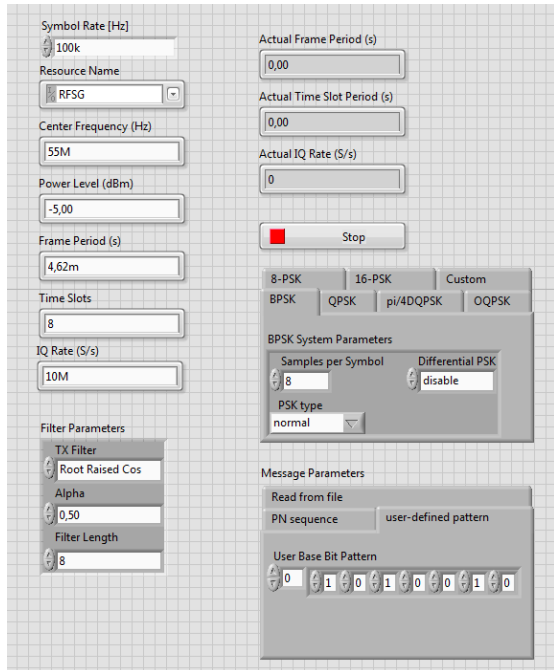

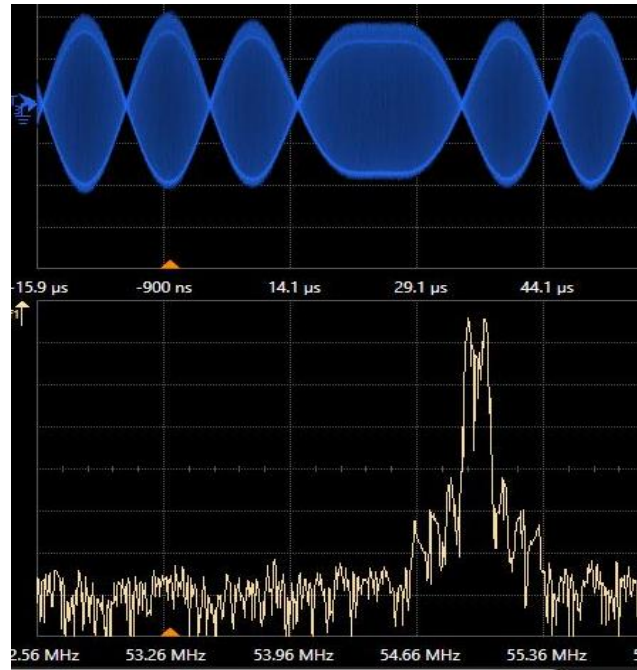**Figure 2.** LabVIEW VI front panel for MST radar signal control.

Figure 3. Spectrum and carrier of the 7-bit phase-code modulated signal of the MST radar.
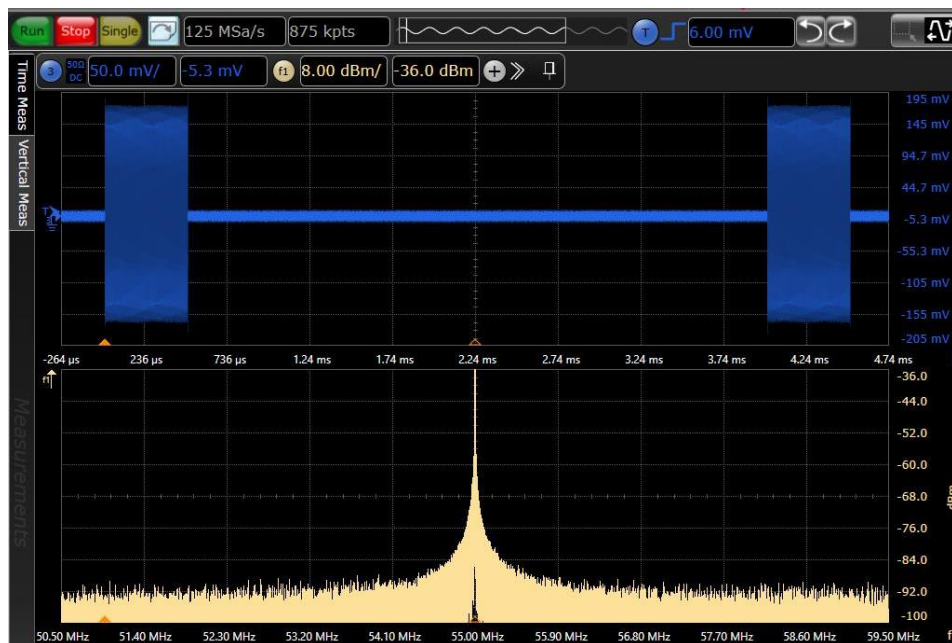

Figure 4. The periodic sequence of radio pulses and their spectrum of MST radar.

The generator made on the PXIe National Instruments modules contains the NI PXIe-7976R (Xilinx K710T) FPGA, the Ni PXIe-5672 vector signal generator, and the Ni PXIe-8880

computational controller (figure 5). The generator made on the PXIe Keysight modules contains the M9300A PXIe reference frequency generator, the M9303A PXIe frequency synthesizer, the M9316A PXIe digital vector modulator, the M9312A pre-amplifier, and the M9314A boost frequency Converter (figure 6).

Figure 5. Appearance of the generator based on the PXIe National Instruments chassis.
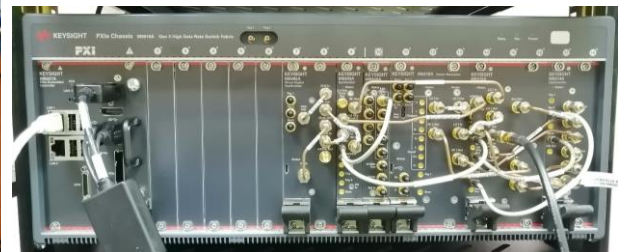

Figure 6. Appearance of the master generator based on the PXIe Keysight chassis.

The principle of interaction of the Keysight vector signal generator modules is shown in the block diagram (figure 7). These software and hardware solutions based on modular elements of PXIe equipment generate sensing signals with the required parameters and the required quality of spectrum purity.
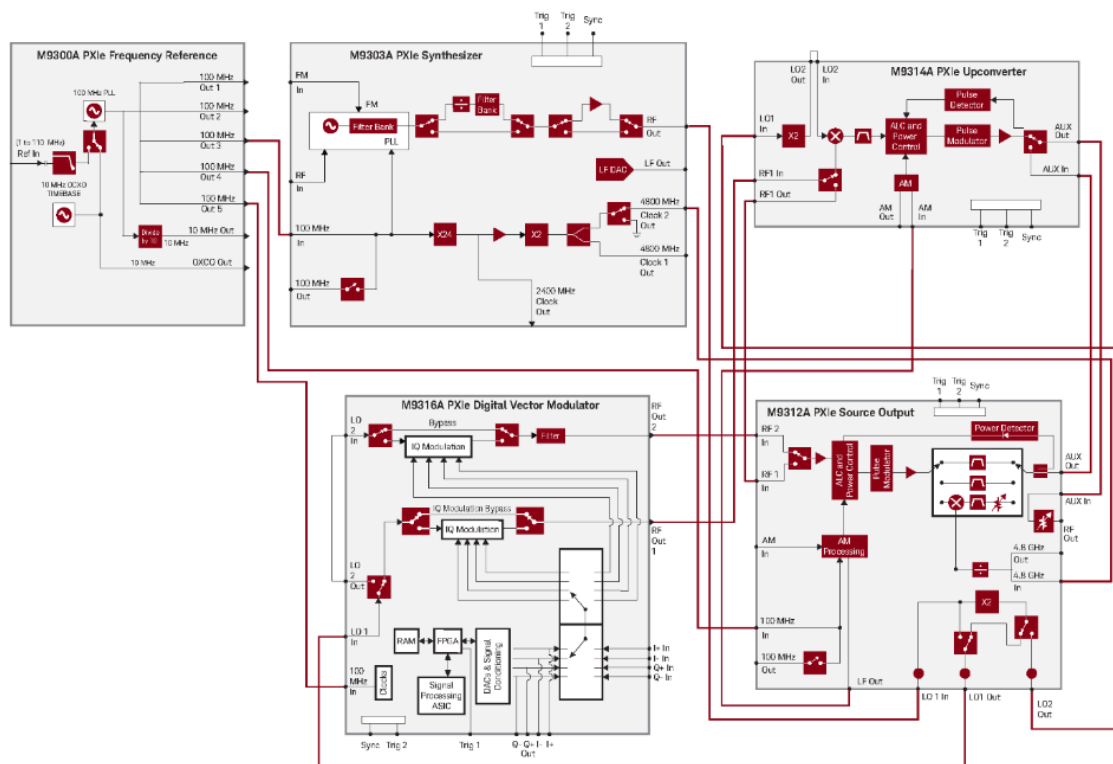

Figure 7. Block diagram M9383A.

4. Conclusion

In that way, these software and hardware complexes based on PXIe National Instruments and Keysight allow generating radio pulses with different modulation and with the required quality. Flexible control of modular elements of the software and hardware complex provides the formation of

a given frequency-code structure, duration, repetition period, power and frequency of emanated radar signals. This control allows performing the specified characteristics of the MST radar (height resolution, sensing range, detection probability, accuracy of measurement of atmospheric inhomogeneities). The hardware implementation with low mass-dimensional indicators, energy consumption in combination with a low-element antenna array has a high mobility of the MST radar and allows complex investigating of various inhomogeneities of the atmosphere and the lower part of the thermosphere using electronic scanning.

Acknowledgments

References

[1]   Zandt T Van 2000 A brief history of the development of wind-profiling or MST radars *Annales Geophysicae* **18** 740–9

[2]   Nishimura K, Nakamura T, Sato T and Sato K 2012 Adaptive Beamforming Technique for Accurate Vertical Wind Measurements with Multichannel MST Radar *Journal of Atmospheric and Oceanic Technology* **29** (12) 1769–75

[3]   Kashcheeva B, Proshkina E and Lagutin M 2002 Remote methods and tools for studying processes in the Earth's atmosphere *Kharkiv national University of Radioelectronics, Business Inform* 426

[4]   Vladimirov V, Karmishin A, Markov V and Shepov V 2014 Digital sounding-pulse generator for UHF MST radar *Proc. 2014 24th International Crimean Conference Microwave and Telecommunication Technology, CriMiCo 2014* (Sevastopol, Crimea; Ukraine; 7 September to 13 September 2014)

[5]   Vladimirov V M, Ratushnyak V N, Vyahirev V A and Tyapkin I V 2019 Features of scanning the atmosphere and building radar stations of vertical sounding with a low-element antenna array *Spacecraft & Technologies* **3** (4) 237–42

[6]   Sokolovskij A V, Vysockij S V, Ratushnyak V N and Gladyshev A B 2017 Analysis of the effectiveness of the VHDL descriptions of the architectures of adders *Sience Intensive & Technologies* **18(12)** 66–8