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HIGHLY RECONFIGURABLE BEAMFORMER STIMULUS GENERATOR

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The present paper proposes a highly reconfigurable beamformer stimulus generator of radar antenna array, which includes three main blocks: settings of antenna array, settings of objects (signal sources) and a beamforming simulator. Following from the configuration of antenna array and object settings, different stimulus can be generated as the input signal for a beamformer. This stimulus generator is developed under a greater concept with two utterly independent paths where one is the stimulus generator and the other is the hardware beamformer. Both paths can be complemented in final and in intermediate steps as well to check and improve system performance. This way the technology development process is promoted by making each of the future hardware steps more substantive. Stimulus generator configuration capabilities and test results are presented proving the application of the stimulus generator for FPGA based beamforming unit development and tuning as an alternative to an actual antenna system.

Keywords: *antenna array, beamforming, LabVIEW, simulation, stimulus generator*

1. INTRODUCTION

Many technical applications before implementation into hardware are tested in the simulation mode achieving very close results to the real-life performance in order to have the desired hardware performance and resource economy, e.g., money, human power, time. Antenna array related technologies, such as radars are no exception and antenna array technologies become more and more common in different areas where their specific functionality is required, also implying that the performance of each component plays an important role in the antenna array system. The performance and characteristics of antenna array technologies are well known and have been studied for a few decades now [1], thus providing the necessary information to enable narrow band signal simulation of a receiver of the phased antenna array system.

The paper describes a phased antenna array stimulus generator, which includes specific parts of the antenna array system – an antenna array with a radio and intermediate frequency (RF/IF) path (LNA, amplifier, filter, mixer and ADC) and a beamformer.

Phased array antennas consist of multiple stationary antenna elements, which are fed coherently and use variable phase or time-delay control at each element to scan a beam to a given angle in space. The primary reason for using arrays is to produce a directive beam that can be repositioned (scanned) electronically [2].

A beamformer is a processor used in conjunction with an antenna array to provide a versatile form of special filtering for antenna array signal samples making the radar sensitive only to the selected direction [3]. Beamformers can be further subdivided into conventional beamformers and adaptive beamformers. Conventional beamformers employ a fixed set of the so-called weighting coefficients to combine signals from the antenna in the array, primarily using only information about the location of the signal of interest (SOI) relative to the antenna array, whereas an adaptive beamformer uses updated information about SOI and unwanted signals to reject them [4]. The paper presents implementation of a conventional beamformer with further development to be improved as an adaptive beamformer.

The most popular simulation environments, such as Matlab, use a sequential signal processing simulation model, graphical environment LabVIEW is convenient when it is to develop a parallel signal processing path[1]. LabVIEW provides a very convenient simulation environment for developing algorithms graphically from the perspective of electrical engineers, which is then well suited for development of simulation codes applicable in the most commonly used hardware for real-time high throughput signal processing – field-programmable gate array (FPGA). The greatest advantages of FPGA are the rapid non-stop technology development – increase in speed and parallel code execution, which will come relevant in the general concept when the hardware part will be developed. In the present paper, a general concept of stimulus generator application is explained, introduction to simulation reconfiguration capabilities provided and results presented.

2. GENERAL CONCEPT

Figure 1 presents the general concept under which the paper is developed. The concept has two utterly independent paths: Simulation path and Hardware path, where both paths can be combined at intermediate steps forming a half-simulated, half-hardware implemented antenna array receiver system. The main purpose of such a solution is to iteratively improve both paths using the simulated and real signals. The implementation of the four main steps for each path is different, but names are the same:

- Antenna array;
- Received signal;
- Beamforming;
- Beamformed signal.

[1] LabVIEW popularity (Accessed: 2 Aug 2017): http://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=LabVIEW.

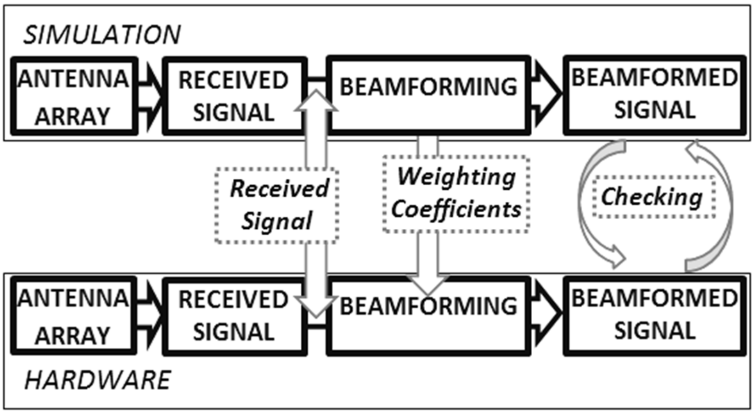

Fig. 1. Block diagram of a general concept.

A. Simulation Path

Simulation path steps are implemented and run in the simulation mode only, which means that characteristics of all the parameters must be simulated after a very close approximation of real-life. More importantly the developed simulation – the stimulus generator and beamforming simulation provide an opportunity to manipulate with each step and characteristics to find the most suitable design, parameters and performance for each individual implementation case and the desired application.

The first step defines the characteristics of antenna array; the second step "captures" the received signals from objects (signal sources) and saves them in a file to make stimulus for the FPGA based beamforming unit. In the third step, the weighting or beamforming coefficients are calculated and also saved in a file. Either of the files – simulated signal and weighting coefficients – can be imported in a hardware beamforming step, thus making it possible to develop FPGA-based beamforming unit signal processing algorithm without having an actual antenna array and an RF/IF path. This way the technology development process is promoted by making each of the hardware implementation steps more substantive.

In the final step, the beamformed signal is calculated approving or disapproving the estimated beamforming results. This is the step where performance of the complete system can be checked. The results of simulation path can be verified with the achieved results of hardware path calculating weighting coefficient corrections and consequently improving the performance of both paths [5].

B. Hardware

Hardware path steps are real-life based implementation, where an antenna array is a physical structure of a greater or a smaller dimension depending on the aim of application. Apart from tuning the beamformer, the received signals are recorded and saved in a file. Saved signals can be imported in the beamforming step of both signal paths to test the beamforming algorithm in both simulation and FPGA-based mode and check whether FPGAbased algorithm is working properly. Moreover, the received real life signals can be used to optimise the signal simulation step results taking into account new real-life signal amplitude-phase characteristics.

The third and fourth steps are utterly FPGA-based where the implementation is performed taking into account FPGA specification and limitations. Having the real-life received signal in the beamforming step of both paths, the beamformed signals can be compared to see if the results are consistent.

According to the topic of the paper from this point forward the paper focuses only on the simulation path.

3. SIMULATION

The simulation is developed in programming environment LabVIEW. The simulator consists of the three main reconfigurable steps (tabs of front panel are presented in Figs. 2–4):

A. Settings of Antenna Array

Here (Fig. 2) antenna array characteristics, such as antenna radiating dimension, antenna array type (regular or irregular), number of antennas and distances between antennas, are set to simulate the desired antenna array.

Calculations regarding an antenna array include x and y coordinates for each antenna into an array (starting from bottom-left corner to top-right corner – through columns). In the case of a regular antenna array, coordinates are calculated from user defined distance between antennas *d(x)* and *d(y)* and the number of antennas per row and column. In the case of an irregular antenna array, coordinates are randomly generated from user defined maximum array length per x and y axis and the number of antennas.

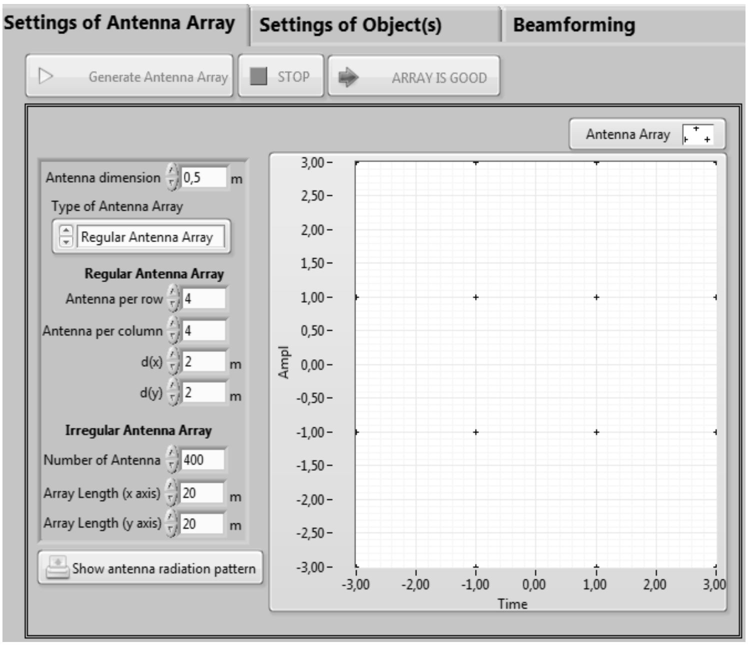

Fig. 2. Front panel of the developed simulation (Step 1).

B. Settings of Objects

In this tab (Fig. 3), characteristics of object or objects to be observed, such as object location, frequency and power, are configured to define the stimulus that antenna array will receive. It is possible to simulate up to four objects simultaneously, but it must be kept in mind that this simulator uses a conventional beamforming method.

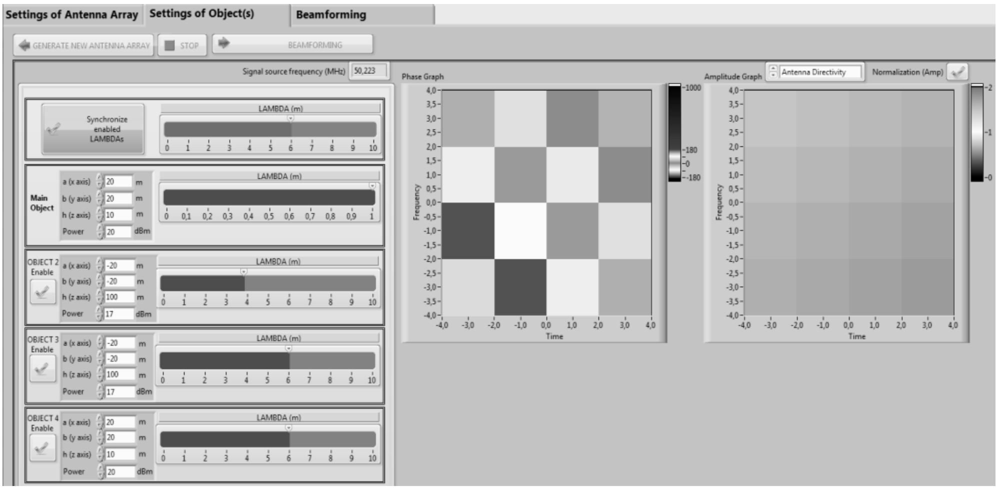

Fig. 3. Front panel of the developed simulation (Step 2).

a. Calculations regarding an Object

The distance between each antenna and object S_{ant} *(x,y)* is calculated by the vector method. First, it is necessary to calculate a' and b' – the distance between each antenna and the object in x-y plane, where *a* and *b* is the distance between the centre of coordination system and the object in *x* and *y* axis, respectively, and $\Delta X(x)$ and $\Delta Y(y)$ is the distance between centre of coordination system and each antenna in *x* and *y* axis, respectively:

$$a' = a - \Delta X(x),\, b' = b - \Delta Y(y).$$

Calculation of distance S_{ant} (x,y) using the distance between each antenna and object a' and b' and height (z axis):

$$S_{ant}(x, y) = \sqrt{a'^2 + b'^2 + h^2}.$$

b. Calculations regarding Antenna Array Signal Amplitudes

The amplitudes (A_i) of the received signals (object radiated power) for each antenna are calculated from an antenna directivity diagram *(D)* and as all antennas are identical dipole antennas they all have the same directivity diagram $A_i = D(a_i', b_i', h_i)$. It is possible to calculate antenna directivity depending on *h* (z axis) value and distance to the object in XY plane.

If $h = 0$ (the object is in XY plane):

$$D = \frac{1}{1 + \left(\frac{b'}{a'}\right)^2}$$

If $h \neq 0$ (the object is not in XY plane):

if $|b'| \geq \sqrt{h^2 + a'^2}$ then

$$D = \frac{1}{1 + \arctan\left(\frac{|b'|}{\sqrt{h^2 + a'^2}}\right)}$$

if $|b'| \leq \sqrt{h^2 + a'^2}$ then

$$D = \frac{1}{1 + \operatorname{arccot}\left(\frac{\sqrt{h^2 + a'^2}}{|b'|}\right)}$$

c. Calculations regarding Antenna Array Signal Phases

The phases for each antenna are calculated from the distance between the object and antenna S_{ant} (x,y) and the object signal frequency (wavelength λ). First the phases are calculated in radians φ_{rad} and then converted in degrees φ_{deg}:

$$\varphi_{rad} = \frac{2\pi \times S_{ant}(x,y)}{\lambda}, \varphi_{deg} = \frac{\varphi_{rad} \times 180}{\pi}.$$

C. Beamforming

In this step (Fig. 4), the generated signals are displayed: the main object signal, the received signals in each antenna, the beamforming signal and the beamformed signal. As an extra, signal path properties for standard deviation of the signal phase and amplitude can be configured.

Beamforming adjusts the amplitude and phase of each antenna array element signal to compensate for the different delays and attenuations associated with signal paths to elements to increase the signal quality in a specific direction of arrival [6]. This simulator has a conventional beamformer, where the weighting coefficients consider only SOI information: the signal amplitudes for each antenna are calculated from the free space path loss (FSPL) and other additional losses in the signal path, which can differ for each system; the signal phases are corrected for each antenna by changing the phase sign of the beamforming signal for each antenna [7].

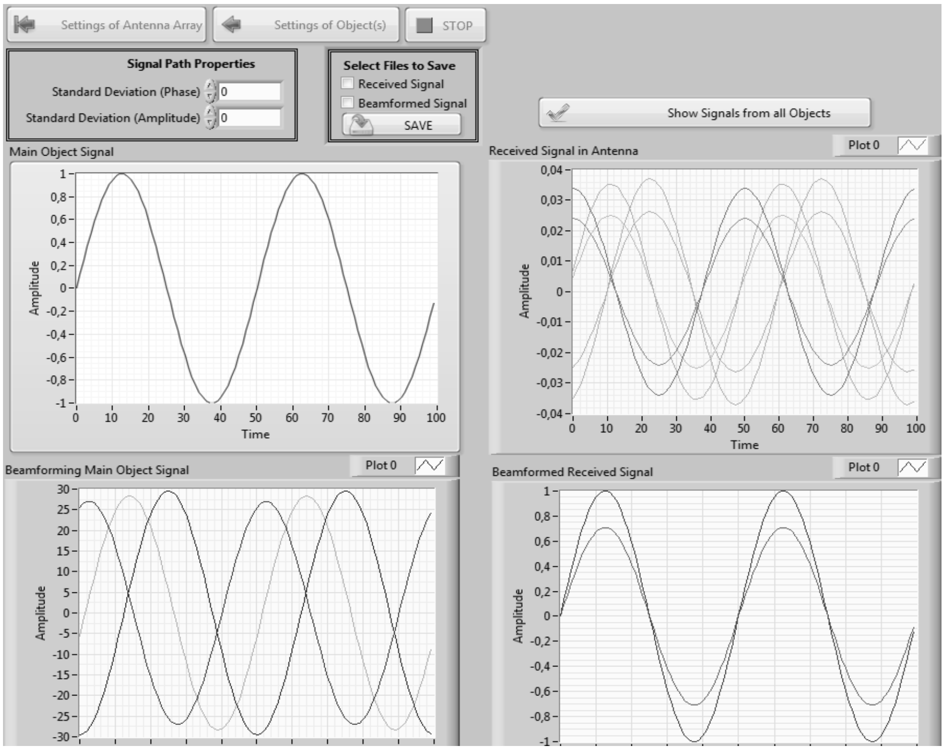

Fig. 4. Front panel of the developed simulation (Step 3).

The concept of the developed simulation is shown in Fig. 5, which demonstrates that the characteristics of stimulus are to be tweaked to represent the desired signals of the antenna array.

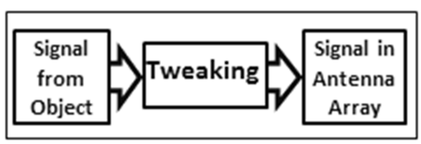

Fig. 5. Block diagram of the simulation concept.

When ready the received signal and beamformed signal can be saved in data files. The saved files contain data of generated signal, weighting coefficients and beamformed signal that can be applied in hardware implementation as a stimulus for checking and improvements of beamformer algorithm hardware implementation.

4. RESULTS AND DISCUSSION

The simulation path has been created by developing the stimulus generator of radar antenna array; the algorithms initially have been tested in LabVIEW simulation mode. The testing is done by analysing the achieved results and saved signal files. All simulation results are shown in the simulation software graphs and indicators allowing one to check simulation model correctness.

The performance of the stimulus generator was evaluated simulating different antenna arrays and checking the generated signals qualitatively and quantitatively. As an example, Fig. 6 demonstrates simulation of a regular antenna array (Fig. 6) with 4 x 4 antennas (numbering starts from bottom-left corner to top-right corner – through columns) with 2 meter distance among antennas. In the array, all the antennas are identical dipoles and positioned in parallel to *y*-axis with radiating dimension of 0.5 meters. The SOI is an object with radiating power of 20 dBm and initially located 5 meters above the centre of XY plane. During simulation, the position of the object is changed for each of the four tests:

1. Position A (meters): x=0; y=0; z=5;
2. Position B (meters): x=5; y=0; z=5;
3. Position C (meters): x=5; y=5; z=5;
4. Position D (meters): x=0; y=5; z=5.

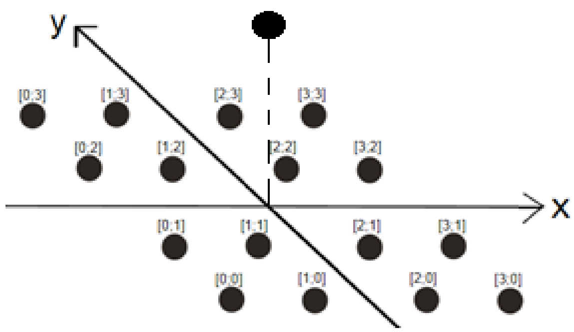

Fig. 6. Signal simulator setup.

The result of this test and, accordingly, the performance of this stimulus generator are shown in Fig. 7, where the characteristics, such as phase and power, in the antenna array are presented. The difference in phase and power when changing the object location meets the expected results, because when object is initially located in the centre of array the antennas located closer to the object in XY plane will have greater power than the ones located further in either of the directions in *x* or *y* axis. The same principle is observed for all four tests. From these results it can be concluded that the signal simulator is working correctly and as expected.

In order to test the inverse-square law in the performance of one antenna array row from the same antenna array setup as previously, five different object locations are set to measure the received power in each antenna in row. The distance between the object and the nearest antenna ranges from 1 to 26 meters and the radiated power of the object remains constant 20 dBm. The result is presented in Fig. 8, where the power over distance decreases with the object being moved further away from the antenna array.

Similar simulations (not described here) can be made to prove the simulation correctness simulating multiple signal sources (up to 4) or random antenna arrays.

Signal Characteristics in Antenna Array								
x axis, m	0		5		0		5	
y axis, m	0		0		5		5	
Antenna No	Power dBm	Phase Deg	Power dBm	Phase Deg	Power dBm	Phase Deg	Power dBm	Phase Deg
00	-28.79	-34.84	-32.37	23.88	-28.25	-147.45	-32.14	76.24
10	-27.90	-86.06	-32.00	-112.32	-29.44	-137.22	-32.67	81.69
20	-27.90	-86.06	-32.00	-112.32	-30.91	-19.37	-33.42	124.07
30	-28.79	-34.84	-32.37	23.88	-32.37	23.88	-34.30	113.78
01	-27.90	-86.06	-30.91	-19.37	-27.23	106.22	-30.58	-25.34
11	-26.77	128.23	-30.38	108.29	-28.69	-127.07	-31.32	111.66
21	-26.77	128.23	-30.38	108.29	-30.38	108.29	-32.32	-37.00
31	-27.90	-86.06	-30.91	-19.37	-32.00	-112.32	-33.42	124.07
02	-27.90	-86.06	-29.44	-137.22	-27.23	106.22	-28.99	146.44
12	-26.77	128.23	-28.69	-127.07	-28.69	-127.07	-30.01	78.48
22	-26.77	128.23	-28.69	-127.07	-30.38	108.29	-31.32	111.66
32	-27.90	-86.06	-29.44	-137.22	-32.00	-112.32	-32.67	81.69
03	-28.79	-34.84	-28.25	-147.45	-28.25	-147.45	-27.64	67.68
13	-27.90	-86.06	-27.23	106.22	-29.44	-137.22	-28.99	146.44
23	-27.90	-86.06	-27.23	106.22	-30.91	-19.37	-30.58	-25.34
33	-28.79	-34.84	-28.25	-147.45	-32.37	23.88	-32.14	76.24

Fig. 7. Generated signal of 2D antenna array.

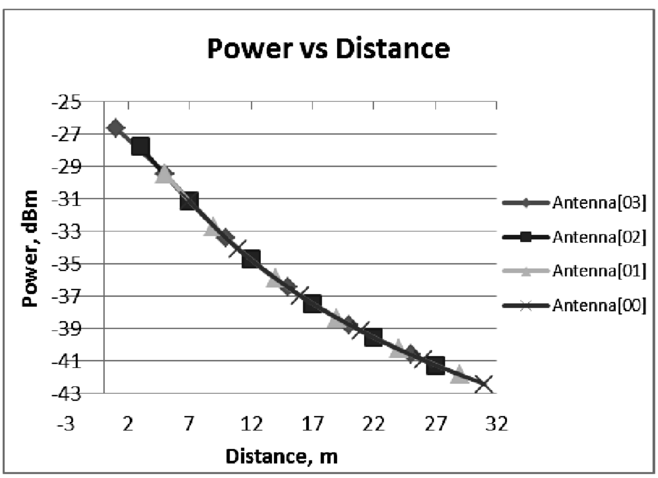

Fig. 8. Power vs distance.

5. CONCLUSIONS

System development in the simulation mode is a very convenient way to test the performance of the system to be implemented into hardware and to promote the progress of hardware design development process. None the less, the simulation mode in any aspect is less resource consumable.

The result of research described is a highly reconfigurable stimulus generator of antenna array receiver that is implemented into National Instruments PXIe1075/8133 platform with the main stimulus generation parameters:

1. Practically unlimited number of simulated antennas;
2. Regular and random placement of antennas;
3. Four different configurable (signal wavelength, power, position) sources of observable objects where one is always the main object and three are unwanted (parasitic noise) signals;
4. Ability to save the generated signals and weighting coefficients of antennas in files.

The stimulus generator is tested and approved by mathematics to be working correctly. It can generate the received signals in an antenna array with characteristics of real-life signals. The generated stimulus and the weighting coefficients can be imported in a hardware beamforming unit, e.g. FPGA-based, to test the hardware implementation without an actual antenna array, which is the main advantage of this simulator. When both simulation and hardware systems are developed, the interaction between these system steps becomes very useful for verification and improvement of both systems.

Future research includes improvement of the simulator by developing an adaptive beamformer and development of a hardware beamformer using National Instruments PXIe-7965R Xilinx Virtex 5 SX95T FPGA Board.

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DAUDZPARAMETRU PĀRKONFIGURĒJAMS STARA FORMĒŠANAS STIMULA ĢENERATORS

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K o p s a v i l k u m s

Pirms praktiski īstenot tehniskos risinājumus resursu taupīšanas nolūkā - tie lielākoties tiek vispirms pārbaudīti simulācijas vidē. Antenu lauka tehnoloģijas tiek pētītas jau vairākus gadu desmitus, tāpēc ir pieejama detalizēta informācija par to darbības principiem un ir iespējams izstrādāt antenu lauka uztvērēja signāla simulāciju stara formēšanai. Šajā rakstā tiek prezentēts daudzparametru pārkonfigurējams stara formēšanas stimula ģenerators un stara formēšanas simulācija. Stimula ģeneratoram var konfigurēt antenu lauka tipu, izmēru, antenas maksimālo fizisko izmēru, antenu skaitu, uztverto objektu skaitu, lokāciju un jaudu, kā arī veikt tā stara formēšanu simulāciju. Simulators ir izstrādāts LabVIEW, kas ir viegli savietojama programmēšanas vide ar FPGA bāzētu aparātnodrošinājumu. Ģenerētos stimulus un antenu signāla korekcijas koeficientus var saglabāt failā, lai vēlāk tos pielietotu, izstrādājot stara formēšanas bloku FPGA bāzētā programmaparatūrā. Tas stipri atvieglo aparatūras staru formētāja izstrādi, jo izstrādātais antenu lauka signālu simulators aizvieto fizisku antenu lauku.

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