

MODELING AND SIMULATION OF AIRBORNE WEATHER RADAR

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This article presents a final thesis; the main objective is to design functional virtual weather radar operating on the basis of mathematical modeling. Although having appropriate support applications is essential. We decided to create a virtual model of airborne weather radar, utilizing a mathematic apparatus and Matlab & Matlab/Simulink software. The main part of the article is devoted to an analysis of reflections in the derivation of mathematical formulas as well as description of the procedures related to design models of various elements of radiolocation chain transmitter - environment – receiver. Finally is shown the most convenient way to implement all the scripts and models built into one simple interface in order to achieve the best and most friendly user environment also for users with minimal knowledge of system conception and Matlab or Matlab/Simulink software skills.

Key words: Weather radar, radar equation, Matlab/Simulink software, graphical user interface.

1 INTRODUCTION

To ensure and maintain desired level of air traffic safety it was necessary to equip specific airplanes by weather radars. Usage and presence of this device on boards of the airplanes is the law. As in any other field of electronics also here an effort is present to improve the system. Main order of improvements is to achieve better properties of the radar system regarding to efficiency, dimensions and weight, but also more reliable detection and display of actual weather data. During almost week long closure of airspace over Europe and the North Atlantic in 2010 weather radar development began to move in the different directions. Nowadays the new prototype of weather radar is tested. Prototype is capable to identify the presence of rocks and volcanic ash particles. This fact suggests that the potential of this device apparently has not been exhausted yet, and it is really worth exploring its other options. The main objective of this paper is to propose virtual functional weather radar, working on principles of the derived mathematical model. Whole conception of the subject is purposefully directed to the education process.

2 MATHEMATICAL MODEL OF AIRBORNE WEATHER RADAR

Base assumption for designing fully working avionic system airborne weather radar model is knowledge of its mathematical apparatus. For this purpose radar equation was derivate. Analysis and synthesis of other equations and mathematical relations of radar technical data was necessary as well. Detailed knowledge of radiolocation principles is essential.

Weather radar is radio technical electronic device which works on principles of primary radiolocation. It means that weather radar algorithm is using modification of basic radar equation:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma_B}{(4\pi)^3 R^4}$$

at which:

P_r – received power, P_t – impulse peak power, G – maximum antenna gain, λ – transmitted signal wave length, σ_B – radar cross section.

During transmitter and receiver implementation problem of mentioned equation has occurred. It was necessary to describe raindrops radar cross section. Since there are no just raindrops, but also hails, snowflakes and water vapors with different sizes and presence in radiated volume. Therefore mathematical definition of weather elements cross section was required. Comparing aircraft's cross section, the weather ones is significantly fluctuating as presence, type and diameter of reflecting elements is changing in volume of the space. Considering microwave C and X band wavelength of radar signal actual cross section of one weather element is described by formula:

$$\sigma_B = \frac{\pi^5}{\lambda^4} |K|^2 D_i^6$$

at which:

$|K|^2$ – Rayleigh backscatter
 D_i – rain drop diameter.

Cross section can be defined also in the other units. One of them is relative reflectance Z often expressed in decibels by following equation:

$$Z[dB] = 10 \cdot \log_{10} \left(\sum_{i=1}^n D_i^6 \right)$$

Other unit can be expression in equivalent amount of total rainfall measured on Earth's surface in millimeter per hour or in imperial units' inches per hour. This relation is designated by mathematical formula:

$$Z \left[\frac{mm}{h} \right] = \left(\frac{10^{\frac{Z[dB]}{10}}}{200} \right)^{\frac{5}{8}}$$

Significant factor which needs to be defined for weather radar equation completion are dimensions of smallest radiated volume. This volume is given by antenna radiation pattern in both horizontal and vertical array θ and ϕ as well as attributes of radiated signal. Most substantial attributes are pulse time τ and pulse repetition frequency (time) T . Minimal distinguishable volume is then defined by formula:

$$V = \frac{\pi \theta \phi R^2 c \tau}{8}$$

Considering all above mentioned facts, relations and equations we are able to write modified radar equation for airborne weather radar:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \cdot \frac{\pi \theta \phi R^2 c \tau}{8} \cdot \frac{\pi |K|^2 D_i^6}{\lambda^4}$$

This equation is representing most essential input parameter which was used in order to propose most realistic and fully functional model of airborne weather radar in Matlab and Matlab/Simulink software.

Matlab/Simulink model of the transmitter

In purpose of transmitter model proposition and simulation we decided to use Simulink. Transmitter model is represented by set of basic Simulink blocks as shown on Fig. 1. Values of block's parameters are the most important of whole weather radar system. They are determining main advantages, disadvantages and attributes of radar and radiolocating signal. All values of block's parameters were set according to values of real weather radar WXR-2100.

Main input blocks are sine wave generator and pulse generator. Its signals are inputs for embedded function block which is representing algorithm of pulse modulator.

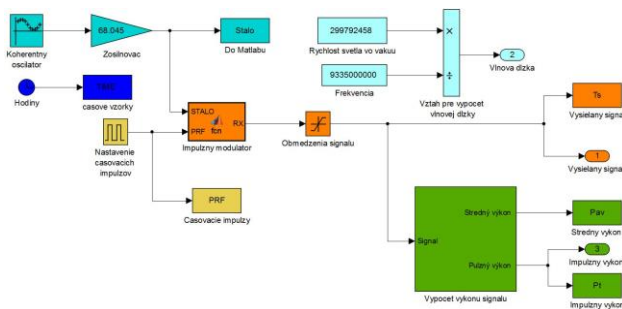


Fig. 1 Transmitter model

Pulse modulator algorithm means that amplified sine wave is transferred to output in time, when clock time is set to value of 1. Otherwise output signal is equal to zero.

Planar array antenna model

Airborne weather radar is using planar array antenna for transmitting of electromagnetic wave into the free space. Directional attributes are described by radiation pattern in both horizontal and vertical array θ and ϕ . In order to compute gain of those antennas, following formula was derivate:

$$G = \frac{4\pi A_g \eta}{\lambda^2}$$

This equation is in Simulink implemented by circuit shown on Fig. 2. Gain and other parameters of the antenna remain constant during all time of simulation run. This is also the reason why we set simulation time to very small value. Output parameter is then vector of constants.

For purposes of next use of computed gain value Matlab script algorithm is used to choose just one of those constants.

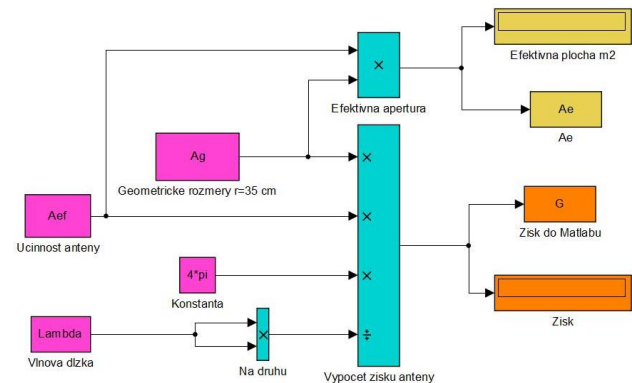


Fig. 2 Gain computing Simulink scheme

Model of space in front of the aircraft

Regardless of the previous two models, the model of weather situation was created. Main properties of this model (radar cross section) will be detected by radar receiver. The main task of this section is to develop a as realistic model of space in front of the aircraft as possible. Model should contain points with cross section properties of water vapor or ice crystals in homogeneities. After initial analysis of the problem and considering or real weather radar parameters few simplifications appeared to be necessary. Subsequent adoption of simplifications was based on reduction of defined space dimensions. Vertical plane was neglected and horizontal was reduced. Final dimensions of considered space were set to 72 x 96 km.

Considering attributes of broadcasted radio wave and main characteristics of antenna beam we calculated minimal distinguishable volume of space to cube with the edge long 150 meters. Practically it meant need of two-dimensional matrix of 480 x 640 points. Values of points corresponded with its cross sections. The most difficult step was to create or autos generate this matrix regarding to shapes and transitions between areas with different parameters of precipitation. Main purpose of this action was our effort to compose as realistic model as possible. As most appropriate tool to achieve this acceptable result of this task graphical method was shown as proper. Method was to create graphical array with defined resolution and color-coded shapes of clouds as well as areas with different cross sections. Proposed Matlab script ensured transformation of graphical bit map to matrix by RGB spectrums analyze. Every single color was represented by value from 0 to 255 for red, green and blue component. Output of whole bit maps-handling process is matrix with various cross section coefficients which express various attributes of space with precipitation particles. Independently to graphical models we computed cross section values by using Simulink model shown on Fig. 3 which is representing cross section equation into Matlab and Simulink environment. Problem has occurred while we tried to assign values to input variables of the model. With this dilemma Slovak

hydro-meteorological institut helped us and provided data gained by practical measurements and observations.

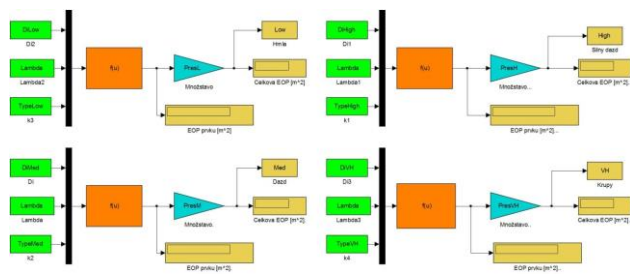


Fig. 3 Cross section computing model

Using Matlab script language we designed cycle for assignment of cross section constants to points of shape matrix. In order to finalize dealing with space and weather matrixes implementation of modified radar equation was required. Practical realization was based on quantification of all equation segments and variables.

Weather radar receiver model

Main task of radar receiver is to process radar signal reflected from targets with different cross sections. In purpose of modeling and modeling of the transmitter we decided to use just Matlab script language. In the beginning we computed distances and angle parameters to all points of the weather data matrix. To do this we used mostly goniometric functions and Pythagoras theorem. Important step was to set maximum scan angle to $\pm 80^\circ$ and minimal radar range due to pulse width and radar recovery time. Process of received power matrix modification can be divided into few main steps. First of them is imitating of receiver sensitivity threshold followed by free space path loss compensation. Second step was represented by calculating of target cross section in units of m^2 , relative logarithmical reflection dBZ and corresponding amount of precipitation measured on Earth's surface in mm/h. Role of next section was to amplify signal and to provide user ability to control gain settings of amplifier. Regarding to standardized color scales for each type of interpretation we defined sensitivity thresholds.

Using these levels defined in the program cycle threshold detection was performed for all data. The resulting matrix has at this stage only a certain number of discrete values.

Virtual display unit

Last stage of whole radiolocation chain of weather data matrix detection is graphical interpretation of simulation results for pilot information. Conceptions of the system automatically generate display types according to specific standard (AWR, dBZ or mm/h). Every single display type binds directly to actual gain setting. If considering just 3 gain settings (Max, Min and Cal) and 3 various display types (according to standards) our weather radar is able to generate 9 different displays of one weather scenario as shown on Fig. 4. Since we proposed three different

models, weather radar can automatically generate 27 displays.

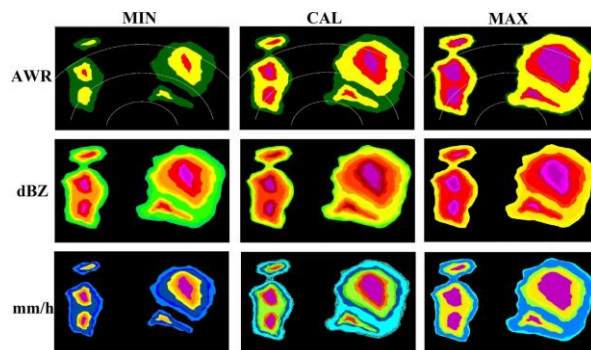


Fig. 4 Various interpretations of thunderstorm weather scenario

3 GRAPHICAL USER INTERFACE

Based on the needs of maintaining the simplicity and intuitiveness of use in the last step we created a graphical user interface. The second reason was to reach friendly control environment with ease of its usage.

Main part of the user interface is virtual display unit placed in the center part of interface window. Around the display unit there are 6 groups of buttons and radio buttons which provide quick control elements linked to constants and variables of the genuine Matlab script. There is also table of static text information which speaks about main parameters of virtual airborne radar system. Window of graphical user interface is shown on Fig. 5 below. Except graphical part of the interface there is also automatically generated Matlab script which must be adjusted according to needs of future user or student. In this point we decided to build interface which will run Matlab and Simulink simulations in real time and get or refresh values of out parameters in every single cycle.

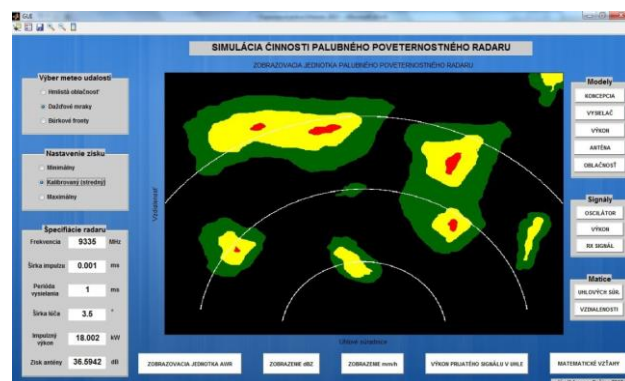


Fig. 5 Graphical user interface window

User is informed about action of interface through message box pop-up windows. For future ease of use and maximal possible compatibility with other computers we exported Matlab files and models into the one .exe file. In order to run this file computer must have

installed Matlab Compiler Runtime version of 8.0 or higher.

4 CONCLUSIONS

In order to complete assignment of the master thesis we built virtual model of avionics airborne weather radar in Matlab and Simulink software. All proposed models and Matlab scripts were together with graphs, pictures, mathematical apparatus and simulation outputs implemented into one simple and modular graphical user interface. Interface was designed with taking into the account that it is going to be used in education process. Therefore GUI meets most of requirements for computed based training software. Regarding to facts mentioned above authors found, that master thesis fulfill all requirements.

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