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SIMULATION TOOL FOR ROC ANALYSIS IN THE CONTEXT OF WEATHER RADAR CALIBRATION

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Abstract:
Weather radars have become an invaluable tool for real time measurements of meteorological quantities such as precipitation rate and wind velocity. For meteorological products to be as accurate as possible, the amount of uncertainty in each estimated quantity must be minimized. A well-controlled calibration process must be used to reduce the influence of imprecisely known radar system parameters on the uncertainty of the formed estimates. There are different calibration methods. This work concerns design of active, external, calibrator for use with weather radar. It presents simulation tool and some initial investigation of the calibration potential capabilities obtained by means of Monte Carlo simulation analysis.

Keywords: *weather radar, calibration, signal processing, simulation.*

1. Introduction

Pulsed weather radars produce estimates of reflectivity, mean radial velocity and velocity spread using echo signal samples from a wide variety of weather targets. Estimates are derived from the parameters of the modified echo signal (amplitude and frequency/phase) scattered from the target back in the direction of the radar. For meteorological products to reflect weather conditions as accurately as possible, the uncertainty of each estimate must be minimized, or accurately characterized. If radar system parameter accuracies are not precisely known, the reflectivity estimate will be biased and thus, assessments of true conditions could be either misleading or masked. A well-controlled calibration process is therefore critical to reduce reflectivity bias due to imprecise knowledge of the radar system parameters. A well calibrated radar should produce, under optimal measuring conditions, accurate base data, i.e. correct estimates of location, reflectivity, radial velocity and velocity dispersion of suitable test targets. The calibration is applied to the radar antenna positioning system and to the radar transmitting and receiving chain. There are different calibration methods, such as: solar and celestial radiative flux transfer, lunar reflectivity, rain gauge comparison, radar calibration targets, transponder [1]. Compared to other calibration methods, use of an external active calibration system is the most reliable, independent and thorough means of calibration [2].

This work concerns design of active, external, calibrator for use with weather radar. MATLAB simulation tool is developed for investigation of Receiver Operational Characteristics (ROC) of the weather radar for signals received from external source. The results can be used to derive characteristics of the potential calibration precision for external active system.

2. Software simulation tool

Before Monte Carlo runs, input parameters that describe the radar system, simulation scenario and input parameters of the tested algorithm are assigned. Then target and environment signatures are generated and complex matrix representing the in-phase (I) and quadrature (Q) channel signals is formed.

The complete algorithm consists of program files which represent separate functions with their own input and output parameters. Each program file can be started independently and irrespective of the other files, but preliminary initialization of its global parameters is necessary. The list of global parameters includes the basic parameters of the signals and the processing algorithms that influence most the authenticity of results.

After execution of the complete algorithm collection of data for each set of SNR is carried out. These data are processed in block for statistical analysis of the ROC. The so obtained results are graphically depicted. An option for 2D and 3D graphical presentation of the results achieved by the execution of the modelled sequence of processing algorithms is also provided.

3. Models of radar signals and algorithms

Calibration of the receiving channel requires the measuring and adjusting of the receiver parameters. For this purpose the active calibrator must be able to reliably simulate a known reflectivity and to produce a known Doppler shift for radial velocity simulation.

For evaluating the quality of different methods and means during the calibrator development, real data must be used, but the optimal approach is the initial investigation of their potential capabilities by Monte Carlo simulation method which corresponds to modern technology for the design of digital information systems. It comprises: simulation of radar signals; simulation of Doppler processor algorithms; data collection and analysis of the signal probabilistic characteristics.

3.1. Models of received signals

In this work the complex envelopes of the additive sums of reflected (according to chosen scenario) signals and thermal noise of the receiver are modeled. These envelopes represent in-phase and quadrature signal channels.The signals are sampled in range by M resolution cells. The samples for each range resolution cell are modelled as a train of K pulses. The so obtained signals are arranged in a $M \times K$ matrix. The useful signal is placed in central range cell.

Phases of the reflected signals are modeled as a sum of uniformly distributed random phase and phase which depend of the pulse sequence number, simulated radial velocity, wavelength and pulse repetition frequency.

The amplitudes of the reflected signals are modeled as the product of three multipliers. The first is the realization of random variable with distribution corresponding to the modeled reflector. The second multiplier is recalculated for each range cell depending on the signal-to-noise ratio (SNR), signal-to-clutter ratio (SCR), receiver sensitivity, maximum detection range, length and number of the range cell. The third multiplier modulates the amplitude in order to simulate the antenna beam pattern. A major problem in modeling of radar signals is adequate choice of distribution of the random amplitude. This work is based on realizations of random variables with distribution functions described in the specialized literature as a representative for the radar signals of interest.

The receiver noise is modeled as white Gaussian noise, ie it is uncorrelated and normally distributed in each channel. Since the I and Q channels are orthogonal and have the same dispersion (receiver sensitivity), the noise amplitude is Rayleigh distributed.

Amplitudes of two types of point targets (occupying the central range cell), namely fast fluctuating (Swerling II) and slow fluctuating (Swerling III) targets are simulated. The first model is often used to estimate the lower bound of the capabilities of different signal algorithms. The second model has a better probability of detection characteristics and more realistically presents reflective nature of the external active calibrator. The amplitudes of the signals are exponentially correlated within the pulse train. The correlation coefficient depends on the target signal bandwidth and the pulse repetition period.

The amplitudes of reflections from ground and sea surface are presented statistically as discrete lognormal random field with two-dimensional density function. For the convenient, model of Gaussian field is first realized. Then non-linear transformation of its values is performed. This approach has been developed in detail by V. Behar [3]. The model of the Gaussian two parametric field is described in [4]. This model is based to the correlation properties of field. Since the field is assumed uniform and anisotropic, its correlation function is product of distance and azimuth correlation. It is exponential and depends on the size of the range, the pulse repetition period and of the corresponding correlation coefficients, which have different values in the modeling of the signals reflected from the sea and that - from ground.

3.2. Algorithms for pulse Doppler processing

Algorithms for pulse Doppler processor which realizes moving target detection are modeled. Part of Doppler filtering algorithms operate in the time domain and using them clutter can be rejected. There are non-adaptive (pulse canceller) and adaptive rejection filters of different orders. The pulse canceller is used for rejection of clutter with radial velocity close to zero and is widely known as binomial compensator. Figure 1 presents the normalized frequency response of first order pulse canceller and Power Spectral Density (PSD) of the signal containing the reflection from immobile (0 channel) and moving (34 channel) objects. The adaptive rejection filter realized multisegment version of Burg's algorithm [5]. It uses reference window of pulse trains from at least two range cells. Burg's algorithm carries out a linear prediction of the disturbance based on the fact that the clutter can be modeled as low-order autoregressive process. The adaptive filter is used for rejection of one or more clutter sources with previously unknown radial velocities. Figure 2 presents the normalized frequency response of the third order adaptive rejector and PSD of the signal containing the reflection from moving (17 channel) clutter and moving (38 channel) target.

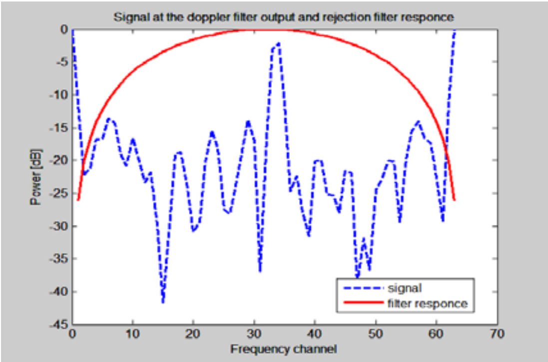

Fig. 1. Frequency response of first order pulse canceller and PSD of the signal containing the reflection from immobile (0 channel) and moving (34 channel) objects

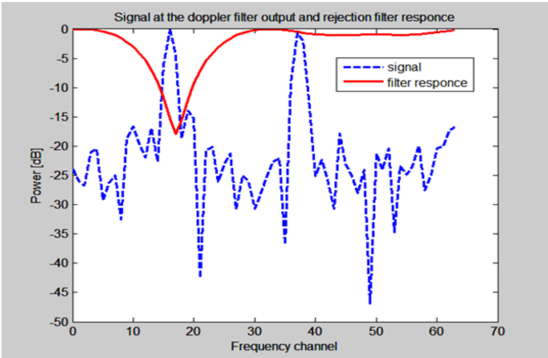

Fig.2. Frequency response of third order adaptive rejector and PSD of the signal containing the reflection from moving (17 channel) clutter and moving (38 channel) target

Figures 3 and 4 present PSD of the modeled signal matrix before and after third order adaptive clutter rejection. The clutter and target central frequencies are located in frequency channels with numbers 17 and 38 respectively.

After clutter rejection, the residual signal spectrum becomes similar to that of white noise. Due to the easy hardware implementation the matched filtering of the signal in noise environment is configured using a Fast Fourier Transform (FFT) as a Doppler filter bank.

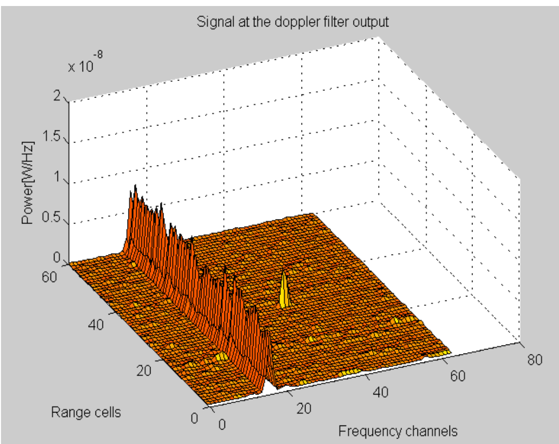

Fig. 3. Signal matrix PSD before adaptive clutter rejection.

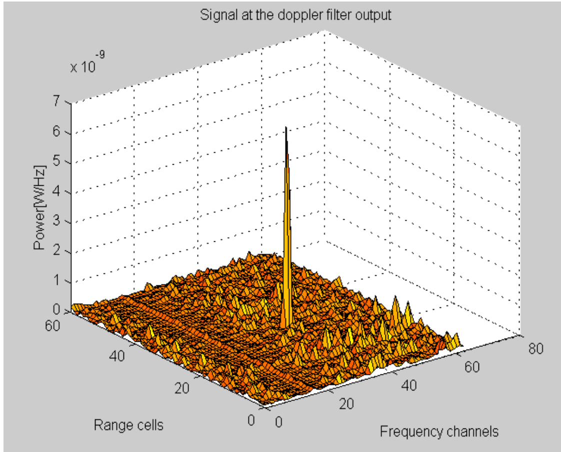

Fig. 4 Signal matrix PSD after adaptive clutter rejection.

Thus automatically, coherent integration is performed and the Doppler frequency of the target (its radial velocity) is estimated. To use the FFT the number of filters is determined as number of power 2, nearest to pulse train length. The outputs of FFT processor are combined in weighted triples to reduce sidelobe responses. Specifically the output of each filter is combined with the pair of adjacent filters by using weights of relative values of 0.23, 0.54and -0.23 (Hamming windowing in the frequency domain). This processing reduces sidelobe responses, but is characterized by a slight reduction and enlargement of the central peak.

A target present or absent decision is made for each range cell by adaptive thresholding, incorporating Cell-Averaging Constant False Alarm Rate (CA-CFAR) technique. Each Doppler channel magnitude is compared to the adaptive threshold. This threshold equals the total sum of the reference range cells magnitudes multiplied by a constant which depends on the designed false-alarm probability and the number of reference cells. Figure 5 presents adaptive thresholds formed for testing range cell and PSD of the tested signal.

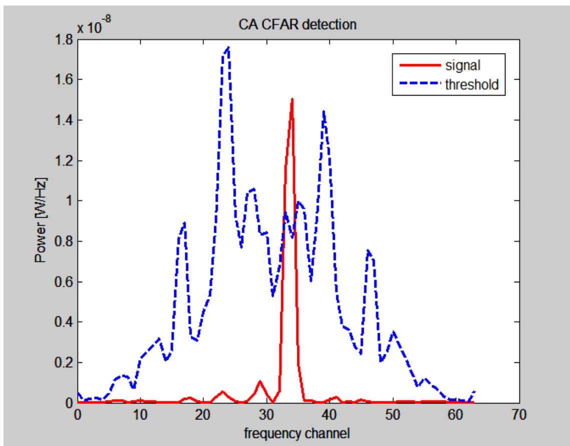

Fig. 5. Adaptive thresholds formed for testing range cell and PSD of the tested signal

Figure 6 presents signal power at the CA-CFAR output. Eight reference cells (surrounding each test cell) formed the adaptive thresholds. The probability of false alarm for each doppler channel is 10^{-6}.

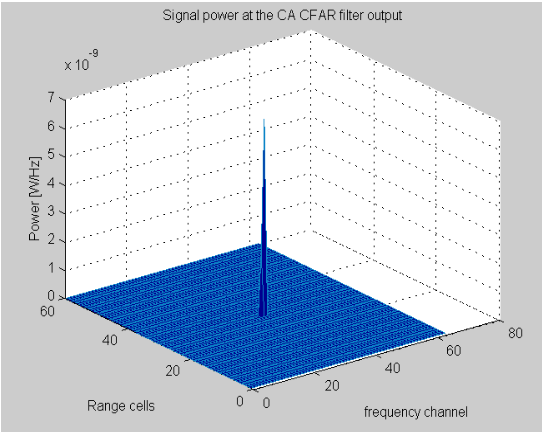

Fig. 6. CA-CFAR target detection

Some results produced using the above presented software tool are presented below.

4. Indicative results

The main objective of the developed software is a simulation analysis of the ROC. Figure 7 shows detection probability characteristics for Swerling II and Swerling III types of target fluctuation in the case of unmoving ground clutter and clutter-to-noise ratio 10 dB. The simulated target radial velocity is 13.5 m/sec. The signal-to-noise ratio varies from 0 dB to 12 dB. For each SNR value simulation experiments is performed 1000 times, then collected data are statistically processed.

The simulated radar parameters are: receiver sensitivity -112 dB; average power of the internal noise 110 dB; antenna beamwidth 1.5°; wavelength 0.10 m; pulse length 1 μsec; pulse repetition frequency 500 Hz. These parameters yield an unambiguous range of approximately 300 km and detection of targets with maximum radial velocity of 26 m/s. The range cell length is 150 m. Range window of 9000 m (60 range cells) is simulated. It is supposed that antenna beam is oriented towards the active target and the number of pulse hits is 50.

First order nonadaptive rejection filter is realized. FFT with 64 frequency channels is used as matched filter bank. A CA-CFAR processor realizes the target detection with 10^{-6} false alarm probability, using 8 reference range cells. In all performed simulations (their total number is 1680000) false alarm is reported in only 3 of them.

As would be expected, for Swerling II the SNR needed to achieve a certain probability of detection (greater than approximately 0.2) is higher than for Swerling III. However, for a detection probability less than 0.2, it is not so, due to the fact that in some realizations Swerling II signal power is greater than the average power.

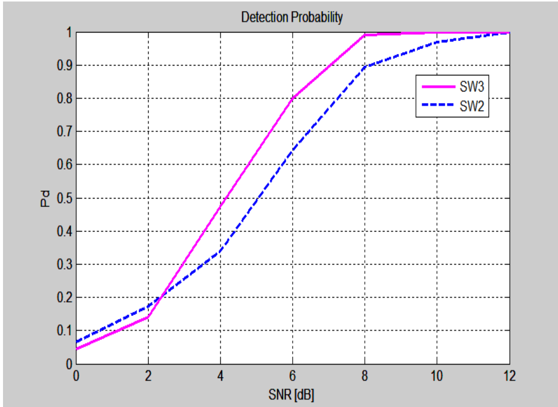

Fig. 7. Detection probabilities

5. Concluding remarks

The above presented simulation tool is convenient for point target detection probability analysis. If the external active target with known reflectivity is used for weather radar calibration, this tool can be useful for potential ROC achievement. Based on these characteristics and theoretical models the potential calibration precision can be estimated.

Acnowledgement

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ПРОГРАМЕН ПРОДУКТ ЗА СИМУЛАЦИОНЕН АНАЛИЗ НА ОПЕРАЦИОННИТЕ ХАРАКТЕРИСТИКИ НА ПРИЕМНИКА НА МЕТЕОРАДАР ЗА ЦЕЛИТЕ НА НЕГОВАТА КАЛИБРОВКА

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