Hardware-In-the-Loop Radar Test Simulator

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Keywords: Radar Simulator, hardware-in-the-loop, Target, Jammer, Clutter

Abstract: In this work, a real-time hardware-in-the-loop (HIL) radar target and environment simulator (RTSim) is presented. RTSim is developed to test the radar systems starting from the initial algorithm development until the final field testing stages. In this way, it is possible to avoid the costly field tests in constantly changing conditions and test the radar systems in a controlled but highly complex environments. In the real-time operation scenario, Radar Signal Processing Unit (RSPU) sends the parameters of the radar signal to the RTSim. For each receive channel, RTSim generates baseband IQ (16-bit I, 16-bit Q) signals using these parameters and user programmed environment including targets, jammers, atmospheric effects, clutter, and radar related system noise. The generated baseband signals are sent to RSPU over fiberoptic lines.

1 INTRODUCTION

The need for real-time simulation tools to test radar systems is increasing in parallel with developments in radar technology. The algorithms used in RSPUs should be justified under real environment conditions prior to the integration with radar hardware. The cost of real environment tests is very high and it is almost impossible to repeat the experiments under the same conditions. Therefore this necessitates the development of a system that simulates the environment in which radar signals travel, and the targets that the radar is trying to detect.

Many of the radar target and environment simulators are designed as commercial products and their implementation details are not disclosed as academic publications (Utteridge, 1987; Saab Sensis, 2013; Intersoft Electronics, 2013; EW Simulation Technology, 2013; Technology Service Corporation, 2013). All of these products are analog simulators that work in the RF (Radio Frequency) or IF (Intermediate Frequency) band and they are not closed loop systems which means that they do not receive the radar parameters in real-time. Another radar target generator that uses FPGAs (Field Programmable Gate Arrays) for baseband signal generation is proposed in (Andraka and Phelps, 1998). Compared to these products, RTSim is a more flexible digital simulator that generates phase-coded baseband IQ signals. All parameters of a radar signal (RF frequency, waveform type, sampling rate, etc.) can be adjusted by radar for each pulse burst waveform.

The components of a typical radar, a test environment and the role of RTSim is shown in Figure 1.

The simulator generates signals whose properties are determined by the radar signal processing units, in the form of baseband IQ. The generated signal will contain all the effects described in the user defined scenario including; targets, jammers, chaff, decoys, environment (clutter and propagation effects), antennas, and radar hardware (amplifiers, mixers, etc.). The generated IQ signal is sent to the RSPUs over fiberoptic lines. In that sense RTSim provides a hardware-in-the-loop test environment that can account for all the effects that a radar signal encounters until it is received by the RSPUs.

2 COMPONENTS OF RTSIM

RTSim consists of a control PC, embedded processors and FPGA (Field Programmable Gate Array) hardware as shown in Figure 2. Control PC has the simulation engine and user interfaces. Simulation engine calculates the navigation and orientation parameters of radar and target platforms in real-time. It uses Digital Terrain Elevation Data (DTED) maps for terrain visualization. All radar and target parameters can be adjusted from the user interfaces.

Target parameters include:

- Position, velocity, route,

Ergezer H., Keskin M. and Gunay O..
Hardware-In-the-Loop Radar Test Simulator.
DOI: 10.5220/0005034506660673
In *Proceedings of the 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2014), pages 666-673
ISBN: 978-989-758-038-3

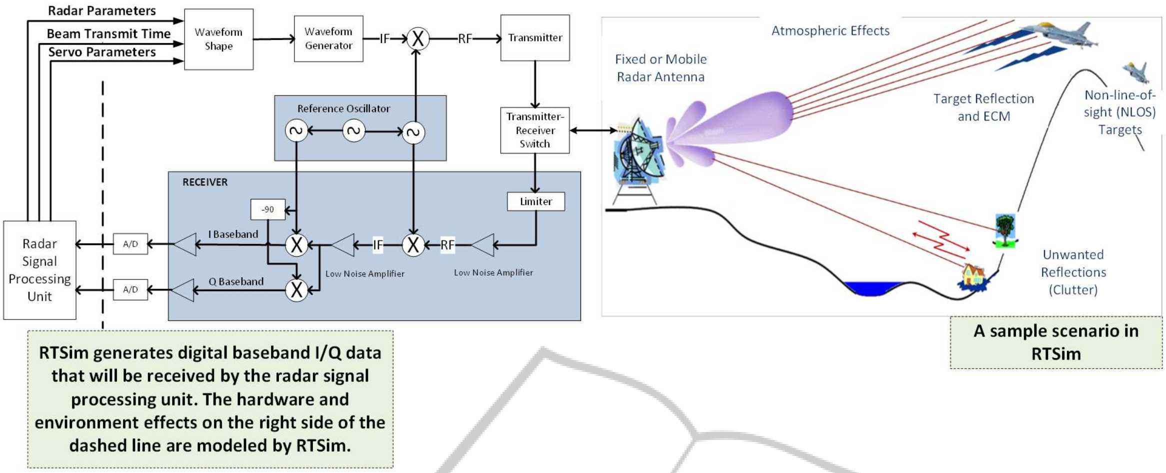


Figure 1: RTSim and radar environment.

- Scatter position and RCS (Radar cross section) parameters,
- RCS type (constant, orientation/frequency dependent),
- Multipath parameters,
- Scintillation parameters (swerling type and correlation time),
- Jammer parameters (noise jammer, deceptive jammer, activation time, etc.),
- Jet engine modulation, helicopter blade modulation.

Radar parameters include:

- Transmitted power, maximum range,
- Antenna scan pattern (circular or RSPU controlled),
- Antenna pattern tables,
- Waveform tables (for phase-coded signals),
- Pulse-repetition-interval (PRI) tables.

Environment parameters that can be programmed from the user interface are: statistical clutter model (distribution type, parameters), atmospheric attenuation and rain attenuation.

Simulation parameters that are adjusted in the user interface are sent to the embedded processors and FPGAs before the simulation starts. Radar and target platforms' navigation information is sent to the embedded processors in real-time. Embedded processors also receive radar beam parameters from RSPUs. The beam message defines the parameters of the radar signal that RTSim generates:

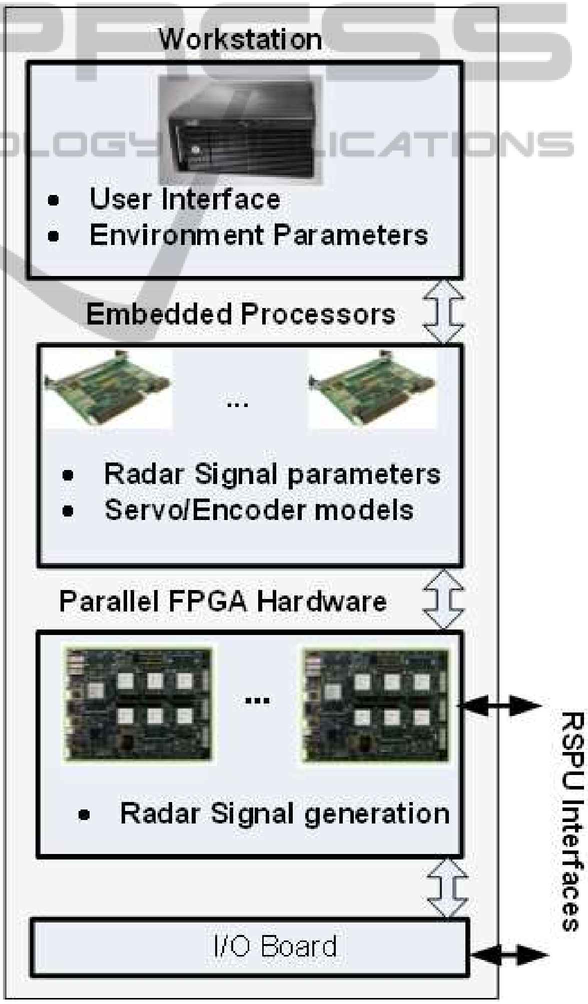


Figure 2: RTSim and radar environment.

- RF frequency and sampling rate,
- Antenna pattern table ID,
- Waveform table ID,

- Pulse Width (PW) and Pulse-repetition-interval (PRI),
- PRI table ID,
- Antenna orientation.

When the beam message is received embedded processors calculate the parameters that FPGAs use for signal generation. Parameters defined in time units (PW, PRI, delay, etc.) are converted to FPGA clock units. Doppler calculations are performed for each platform. Channel attenuations for each platform, jammers and clutter are calculated and sent to the FPGAs. Servo and encoder model calculations are also performed by embedded processors to determine the orientation of the radar antenna. Encoder model controls the fixed speed circular motion of the antenna, whereas servo model is for the RSPU controlled motion of the antenna.

FPGAs generate the radar signals using the parameters sent by the embedded processors. Radar signal generator, receiver channels, clutter distribution generators, system noise generator, jammer noise generators are all implemented in the FPGAs.

3 RTSIM MODELS

3.1 Target Modeling

Radar target generation approaches in the literature has focused on statistical modeling of target RCS. Jet Engine Modulation (JEM) and Helicopter Blade Modulation (HBM) effects are also studied for moving target identification (Sandhu and Saylor, 1985; Carriere and Moses, 1988; Bell and Grubbs, 1993; Phu et al., 1995). In RTSim, targets are modeled as independent multiple scatters with different dynamic RCS tables. When the orientation of the target changes, the relative position of each scatter with respect to the radar changes.

Dynamic RCS of targets is modeled by using the RCS value that corresponds to the orientation (yaw, pitch, roll) of the target. JEM and HBM are modeled using correlated complex Gaussian distributed signals. Target scintillation is modeled by four Swerling models (Richards, 2005). Doppler effect is modeled by adding an additional doppler phase value to the phase codes of the radar signals at each clock cycle of the FPGA.

Doppler speed, which is the velocity component of the target in the direction of the radar, can be calculated as follows:

$$\begin{aligned} V_D &= V_x\cos(\phi)\cos(\theta) \\ &+ V_y\sin(\phi)\cos(\theta) + V_z\sin(\theta) \end{aligned} \qquad (1)$$

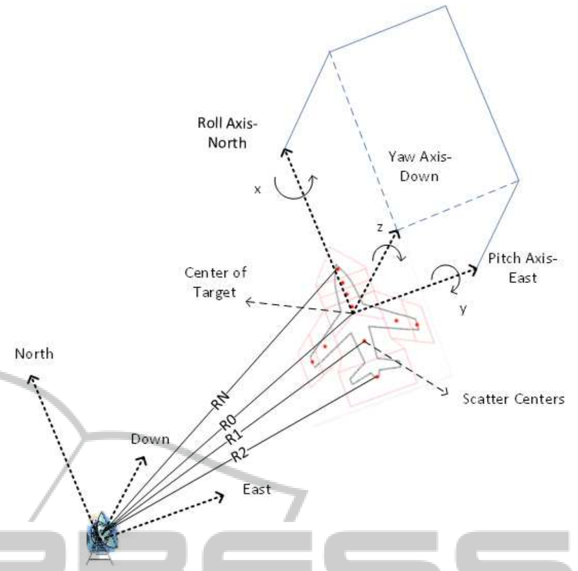


Figure 3: Multiple scatter modeling.

where ϕ is the azimuth and θ is the elevation angle between radar and the target. Doppler frequency is calculated using RF frequency (f) and speed of light (c) :

$$f_D = \frac{2f|V_D|}{c} \qquad (2)$$

The doppler phase value should be incremented at specified intervals that depend on the doppler frequency, to give the doppler effect. The doppler phase is incremented by a specific amount at specific intervals. The interval and increment values and the sign of the velocity are sent to the FPGA as doppler parameters for each beam message. The interval is calculated as the number of FPGA clock cycles:

$$p_c = \left\lfloor \frac{f_s \times k}{f_D(2^{nb}-1)} + 0.5 \right\rfloor \qquad (3)$$

where f_s is the sampling frequency, k is the increment value, nb is the number of bits of the phase codes. The value of k that gives the best frequency resolution is determined by the following optimization:

$$k = \arg\min_x \left| \frac{f_s \times x}{f_D(2^{nb}-1)} - \left\lfloor \frac{f_s \times x}{f_D(2^{nb}-1)} + \frac{1}{2} \right\rfloor \right| \qquad (4)$$

where $x = 1, \ldots, 100$.

Multipath effects are also modeled in RTSim. Three multipaths can be used for each target platform. Multipaths are modeled in the same way as the targets but they have different complex attenuation constants that depend on reflection angle, radar frequency and the reflection surface (Skolnik, 2008).

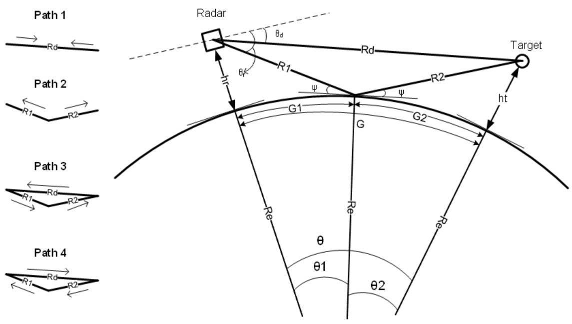


Figure 4: Multipaths.

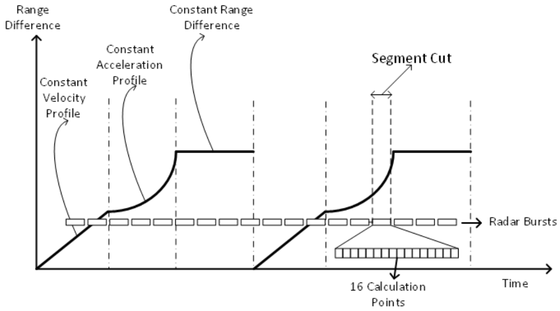


Figure 5: RGPO scenario.

For each receiver channel the received power from a target platform is calculated as follows:

$$P_r = \frac{P_t|K_1|^2|K_2|^2\lambda^2\sigma}{(4\pi)^3 R_d^4 L_s} \quad (5)$$

where P_t is the transmitted power, K_1, K_2 are transmit and receive antenna gains, λ is the wavelength, σ is the RCS, R_d is the distance between radar and target, and L_s denotes the losses (polarization, atmospheric, rain). Using the received power the channel attenuation is calculated as follows:

$$C_A = e^{-j4\pi R_d/\lambda} \times e^{j(\angle K_1 + \angle K_2)} \times \sqrt{\frac{P_r}{D_{P_r}}} \times D_{SG} \quad (6)$$

where D_{P_r} is the default received power that corresponds to the quantized signal amplitude D_{SG}. These two parameters are used to adjust the dynamic range of the 16-bit baseband IQ signal.

3.2 Jammer Modeling

The purpose of electronic warfare is to control the electromagnetic spectrum. RTSim employs different electronic attack (electronic counter measures) techniques to test the radar's performance under difficult scenarios. RTSim models spot, barrage, swept spot noise jammers, and Range/Velocity Gate Pull off/in (RVGPO/I) deception techniques (Schleher, 1999; Kalata and Chmielewski, 1997; Greco et al., 2006; Neng-Jing and Yi-Ting, 1995; Jing et al., 2011; Townsend, 2008). Antenna gain, transmitted power, bandwidth and center frequency parameters can be adjusted for noise jammers. For swept spot noise different frequency patterns can be defined.

RGPO is implemented by adjusting the delays and PRIs of pulse burst radar waveforms. A sample RGPO scenario is given in Figure 5. When VGPO is applied, velocity difference profile is defined instead of range difference. For each burst, range or velocity pull off/in amounts are calculated at 16 different points in the burst. It is observed that this resolution is satisfactory for 200 MHz sampling rate.

RGPO range difference from the beginning of a segment is calculated as follows:

$$R_F = R_0 + S_R\left(V_R \times t + \frac{1}{2}a_R \times t^2 + \frac{1}{6}J_R \times t^3\right) \quad (7)$$

where t is the time since the beginning of the segment, R_0 is the initial range difference, S_R is the sign of the range pull (off=1,in=-1), $V_R(m/s)$ is the pull velocity, $a_r(m/s^2)$ is the pull acceleration, $J_R(m/s^3)$ is the pull jerk, and R_F is the final range difference. For each pulse burst the RGPO segment is determined and R_F values are calculated. Using these values PRI difference values that will be added to the radar PRI are calculated as follows:

$$\Delta P(m) = \left\lceil \frac{2(R_F(m) - R_F(1))}{c} \times F_s \right\rceil \quad m = 1,..,M \quad (8)$$

where c is the speed of light, F_s is the sampling rate. The delay for the generated RGPO/I signal is calculated as follows:

$$D = \left\lceil \frac{2R_D + 2R_F(1)}{c} \times F_s \right\rceil \quad (9)$$

where R_D is the distance between the radar and the jammer. These calculations are performed on the embedded processors and the results are sent to the FPGAs.

VGPO velocity difference from the beginning of a segment is calculated as follows:

$$V_F = V_0 + S_V\left(V_V \times t + \frac{1}{2}a_V \times t^2\right) \quad (10)$$

where V_0 is the initial velocity difference, S_V is the sign of the velocity pull (off=1,in=-1), $V_V(m/s^2)$ is the pull velocity, $a_V(m/s^3)$ is the pull acceleration, and V_F is the final velocity difference. Using these differences "phase counter (Φ_C)" and "phase increment (Φ_N)" values are calculated:

$$f_D(m) = \frac{2f_{RF} \times |V_F(m)|}{c}$$
$$\Phi_C(m) = \left\lceil \frac{F_s \times \Phi_N}{f_D(m)(2^{nb}-1)} \right\rceil \quad (11)$$

where f_D is the doppler frequency, f_{RF} is the radar RF frequency. VGPO is modeled by changing the phase of the baseband signal. After $\Phi_C(m)$ clock cycles phase difference is increased by Φ_N

Coordinated RVGPO/I signal generator is shown in Figure 6. For coordinated implementation parameters should be set as $V_0 = V_R$, $V_V = a_R$, and $a_V = J_R$. The same signal generator can be used to generate target signals as well.

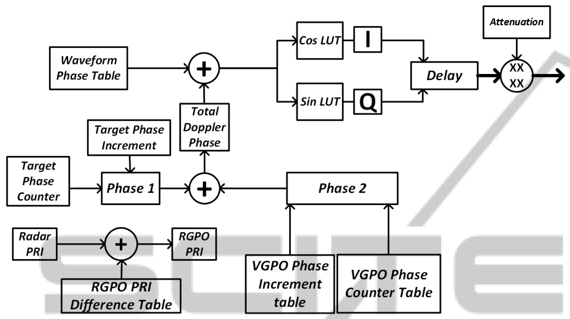


Figure 6: RVGPO/I Signal Generator.

3.3 Clutter Modeling

RTSim implements statistical clutter models. Rayleigh, Weibull and K-distributions are supported. In Figure 7 a typical clutter scenario is described. For each clutter patch a random number is generated corresponding to its range bin. The attenuation for clutter signal is determined by the patch area, grazing angle and distance from radar. The parameters of the random distributions depend on the grazing angle, polarization, radar frequency, surface's dielectric constant and conductivity.

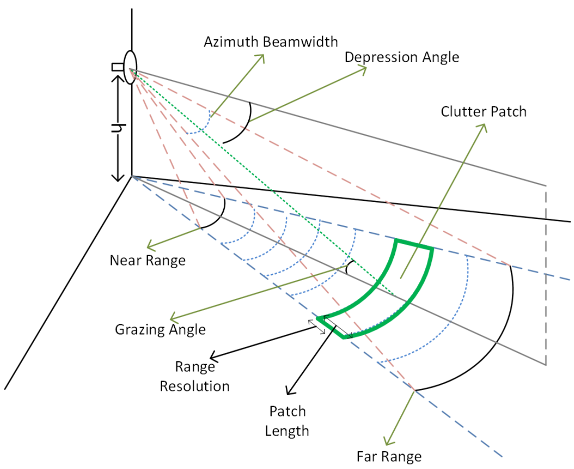


Figure 7: Clutter Scenario.

Random clutter samples are generated using inverse CDF (Cumulative Distribution Function) method. In this method CDF of the distribution is generated as a table, then a uniform number is generated in the interval [0 1], the index of the CDF table that this number falls into is selected as the desired random number. The FPGA implementation of clutter distribution generator is shown in Figure 8. CDF table contains 255 elements of 32-bit numbers which are obtained by quantizing the CDF function of the distribution. Uniform numbers are also 32-bits and the generated random numbers are 8-bits.

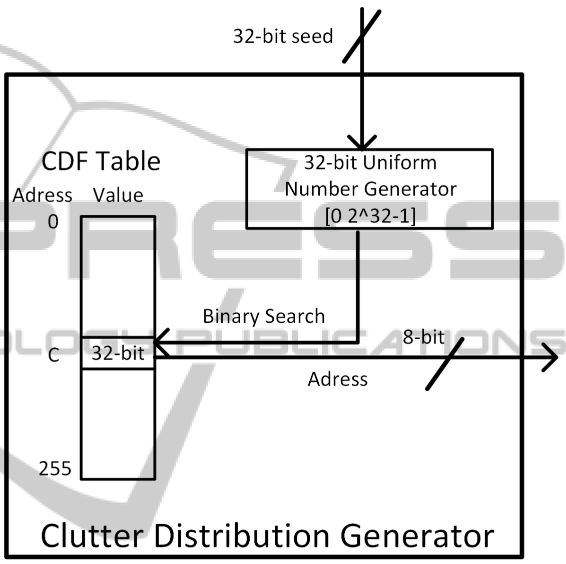
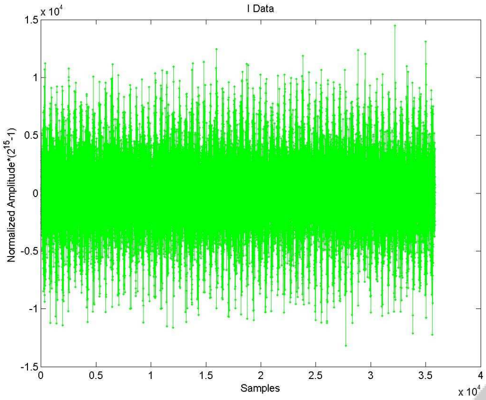


Figure 8: Clutter Distribution Generator.

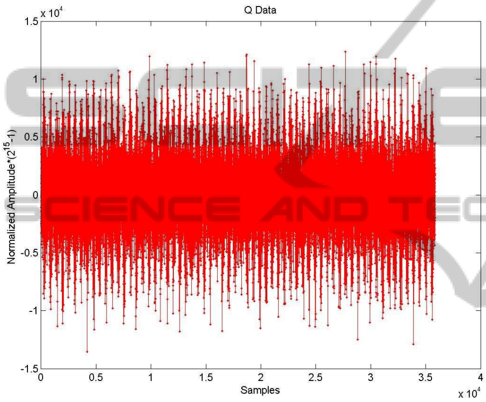
4 EXPERIMENTAL RESULTS

In the experiments the IQ signals generated by the FPGAs are compared to the theoretical calculations. In the first example there are four targets at distances 1343, 1460, 1656, and 1814 meters and moving with speeds 29.83, -309.10, -347.19, -833.52 m/s. The radar parameters are, $PRI = 560$ samples, $PW = 100$ samples, number of pulses in each burst is 64. In Figure 9 the I and Q signals generated by the simulator are displayed. These signals are analyzed using range doppler matrices. The ranges and velocities of detected targets are shown in Figure 10. The results agree with the input parameters.

In Figure 11 sample RGPO and target signals are given. For this example range gate pull of is applied with $V_R = 500\ m/s$. Radar signal parameters are; PRI $= 100\ \mu$s, pulse width $= 20\ \mu s$, chip width $= 200\ ns$, number of pulses $= 500$ and sampling rate = 10 MHz. As seen in the figure in approximately 1.5 seconds 50 samples pull off is applied, and this corresponds to 750 meters range difference at 5 μs.



(a) I



(b) Q

Figure 9: I and Q samples for four targets.

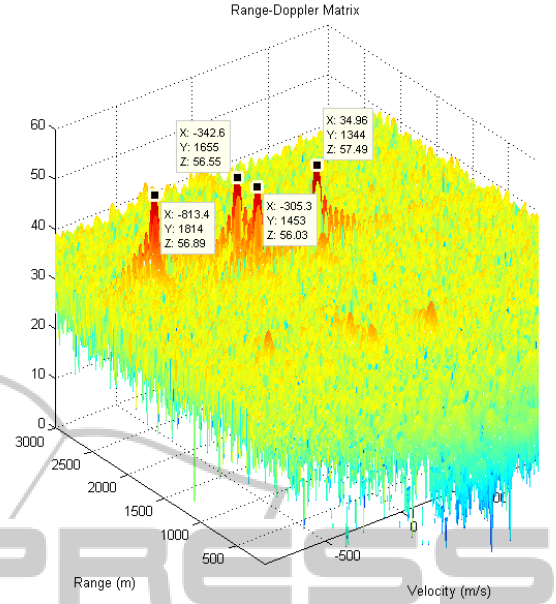


Figure 10: Processed pulses for four targets.

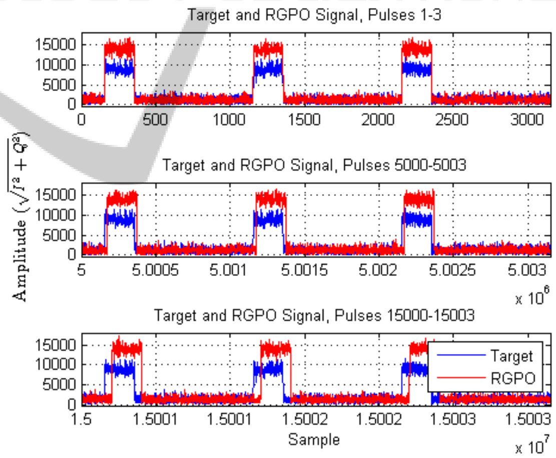


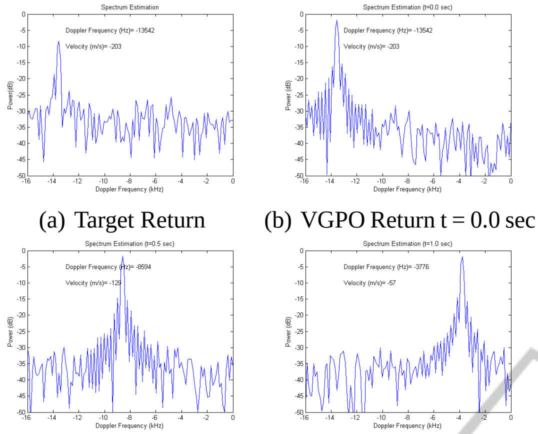
Figure 11: Sample RGPO application. Scenario initialization, after 0.5 ve 1.5 seconds.

In Figure 12 spectrum estimations for target and VGPO signals are displayed. For this example a velocity gate pull off profile with $V_V = 150$ m/s^2 is applied. Radar signal parameters are; PRI= 30 μs, radar frequency = 10 GHz, number of pulses = 128, and sampling rate = 200 MHz. Using these parameters the maximum unambiguous velocity is 250 m/s, and velocity resolution is 7.8 m/s. As seen from the figure in 0.5 seconds the pull off rate is 71 m/s, and in 1 second it is 143 m/s, which are consistent with the VGPO profile.

In Figure 13 the RGPO signal generated by RT-Sim is analyzed and the results are compared with the real constant acceleration profile. RGPO constant acceleration parameter is set to $a_R = 1000\ m/s^2$. The generated signal has 10000 bursts each of which has a pulse of 100 μs. The sampling rate of the signal is 10 MHz. As can be seen from the figure, the generated signal's profile is consistent with the actual profile except for some quantization errors.

In Figure 14 the VGPO signal generated by RT-Sim is analyzed and the results are compared with the real constant acceleration profile. VGPO constant acceleration parameter is set to $a_V = 1000\ m/s^3$. The generated signal has 130 bursts each of which has 128 pulses of 30 μs. As can be seen from the figure, the generated signal's profile is consistent with the actual profile except for some quantization errors.

The final experiment is clutter generation. K-distributed clutter with parameters shape = 4 and scale = 2.06 is generated. Radar signal has four pulses each with 10k samples at 40 MHz sampling frequency. In Figure 15(a) amplitude of the generated clutter samples is displayed. The histogram of the samples is analyzed and compared with the histograms



(a) Target Return (b) VGPO Return t = 0.0 sec

(c) VGPO Return t = 0.5 sec (d) VGPO Return t = 1.0 sec

Figure 12: Sample VGPO Application.

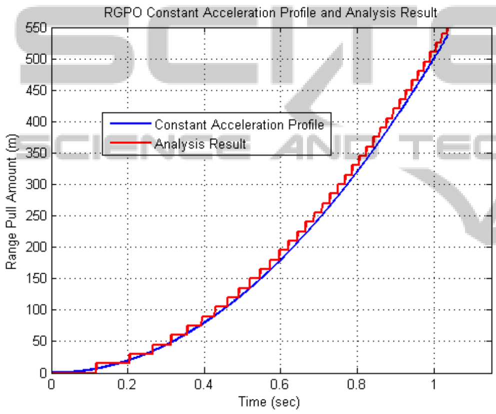


Figure 13: RGPO constant acceleration profile and analysis result.

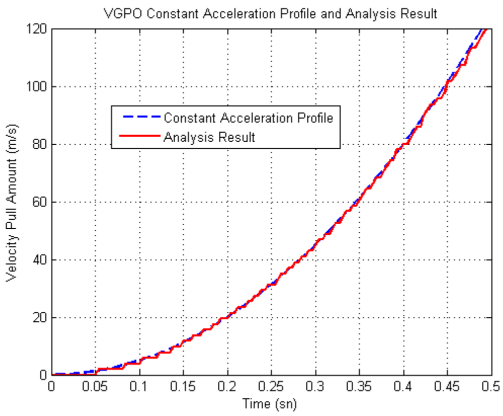
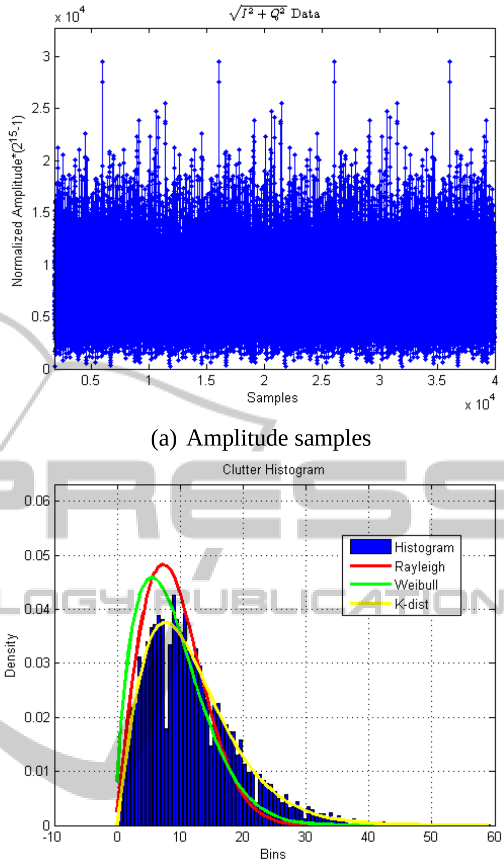


Figure 14: VGPO constant acceleration profile and analysis result.

of Rayleigh, Weibull and K-distributions and then the closest histogram is selected as the true histogram. The estimated parameters are shape = 4 and scale = 2.11 which are in close agreement with the true parameters. Histogram plots are shown in Figure 15(b).



(a) Amplitude samples

(b) Histogram

Figure 15: Amplitude and histogram samples for clutter.

5 CONCLUSION

In this work, a real-time hardware-in-the-loop radar target and environment simulator, RTSim, is described. The simulator can be used to test radar signal processing units even during the early stages of development. RTSim models moving and stationary targets, radars with multiple receiver channels, jammers, statistical clutter returns. RTSim is currently being used in some radar development projects in Turkish Defence Industry. Future work includes implementation of terrain-dependent more realistic clutter models and atmospheric propagation models.

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APPENDIX

Hardware components of RTSim (white rack) and interface simulator for RSPUs (gray rack) is shown in Figure 16. RSPU interface simulator is developed to test RTSim before integration with actual radar systems.

Figure 16: RTSim and RSPU-IS hardware components.