Concepts for Radar Target Simulation

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Abstract

With increasing radar activities in the automotive, industrial and private sector there is a need to test radar sensors in their environment. A radar target simulator can help to test radar systems repeatedly. In this paper the authors present two concepts of low-cost hardware for radar target simulation. The theoretical foundations are derived and analyzed. A schematic for implementation is given.

Keywords: Matching network, SMA, coaxial, microstrip, connector.

1 Introduction

Radar technology was invented in 1904 and is well-known for more than one century. Nevertheless it has mainly been used for military and air traffic over seventy years. Radar systems often were bulky (hollow waveguide plumbing) and expensive. Starting in the seventies radar has been investigated for non-military application. In the nineties radar was firstly used for automotive applications like adaptive cruise control (e.g. by Toyota (1997), BMW (1998), Mercedes (1999)). Starting from that point radar technology became cheaper and easier to fabricate due to the development in semiconductor technologies and material development (RF substrates, interconnection technology, etc.) for even higher frequencies. Actually radars are also applied for industrial purposes (e.g. automation and measurement applications) and personal safety reasons (e.g. in the car interior[1]). The testing of a radar system is not easy. Mostly radars under test (RuT) are tested with real targets like radar reflectors, other cars, passengers, etc. These tests are often not reproducible especially when driving around to test radar systems. There is a need for radar target simulators to allow extended testing of radar systems.

The term ”radar target simulator” has two meanings:

1. a software analysis tool in order to simulate the reflection on a target in a computational environment, [10][2][3]. For the software based analysis there is no need for a real radar system. The radar system must be modeled in the software.

2. a hardware tool as a device [4] which is able to receive the transmit power of a RuT, modifies it and send it back towards the RuT so that an artificial target is detected in a predefined distance in front of the RuT.

In this paper the RaTaSim means the hardware-based device and the author gives a theoretical abstract for two concepts of hardware-based radar target simulation which is missing in some actual publications [4] and one proposal how to implement such hardware as a low-cost variant.

2 Theoretical foundations

In fig. 1 the schematic setup for radar target simulation is given. Only continuous-wave (CW) radars (frequency-modulated or classical Doppler CW) will be investigated here. On the right side the radar under test (RuT) including an internal signal source (e.g. at 24 GHz), an amplifier, a mixer and RX and TX antennas is shown. At a distance \( R_{meas} \) the RaTaSim is located. It receives the RuT signal, modifies it and sends it back towards the radar under test. The RuT has a double side-band downconverting mixer. It can also be supposed to have a single side-band mixer (I and Q channel).

![Fig. 1: Schematic overview about RuT operating with a RaTaSim](image)

Let the line between RuT and RaTaSim be defined as x-axis with \( x = 0 \) at the RuT. The transmit signal from the TX antenna is

\[
y_{\text{RuT}}^{(TX)}(t) = A \cdot \cos (\omega_{\text{RuT}} \cdot t + \varphi_0)
\]

assuming that the frequency is firstly not varying over the time but which will be done later. The actual phase \( \varphi_0 \) includes the phase at the time \( t = 0 \). The received signal when reflected back from a real target in the scenery is

\[
y_{\text{RuT}}^{(RX)}(t) = B \cdot \cos (\omega_{\text{RuT}} \cdot (t - T_{OF}) + \varphi_0)
\]

The amplitude \( B = k \cdot A \) can be derived by the radar equation which includes the path losses, the radar cross section of the
target, atmospheric damping and the angle-dependent gain of the RX and TX antennas. The calculation of B is of no interest here. \( T_{OF} = 2 \cdot R_{Target} / c_0 \) is the time-of-flight of the signal which travels with speed of light \( c_0 \).

Mixing down the transmit signal \( y_{RuT}^{(TX)} \) with the receive signal \( y_{RuT}^{(RX)} \) and a subsequent low-pass filtering yields the baseband (BB) output signal of the RuT

\[
y_{RuT}^{(TX)}(t) \cdot y_{RuT}^{(RX)}(t) = \frac{A \cdot B}{2} \cdot \cos\left(\omega_{RuT} \cdot t + \varphi_0\right) - \cos\left(\omega_{RuT} \cdot (t - T_{OF}) + \varphi_0\right) \\
\rightarrow y_{RuT}^{(BB)} = C \cdot \cos\left(\frac{2 \omega_{RuT}}{c_0} \cdot R_{Target}\right)
\]

It is obvious that when \( \omega \) is changing linearly (linear FMCW-ramp) the output of RuT is oscillating for a non-moving target. The further away the target the oscillation of the RX signal due to the linear FMCW ramp becomes faster. A classical Fourier transform allows for separation of different targets at different ranges. A radar target simulator must simulate the same wave propagation so that the output of the radar yields the same signal described in equation. 4.

### 2.1 Radar Target Simulator with out-of-band source

Let us assume that the RaTaSim consists of an internal RF source which is very stable at frequency \( \omega_{RTS} \) (e.g. PLL-locked). Fig. 2 shows the schematical setup of the RaTaSim.

![RaTaSim schematic](image)

**Fig. 2:** Schematic overview of RaTaSim

The frequency of the source is not in the band of interest (e.g. \( \omega_{RTS} = 23.8\,\text{GHz} \) for the 24GHz ISM band).

\[
y_{RTS}^{(int)}(t) = C_{int} \cdot \cos\left(\omega_{RTS} \cdot t + \varphi_{RTS}\right)
\]

The source signal has not to match the transmit signal frequency of the RuT. The receive signal of the RaTaSim is

\[
y_{RTS}^{(RX)}(t) = C_{RX} \cdot \cos\left(\omega_{RuT} \cdot t + \varphi_0\right)
\]

being \( C_{int} \) and \( C_{RX} \) the internal amplitudes of the signals. Both signals are mixed over a double-sideband mixer yielding only a real baseband signal after low-pass filtering. This signal is of "low" frequency somewhere between DC and several GHz. The complete signal is delayed by a "low-frequency" baseband delay line. The delayed signal is again upconverted over a double-side band mixer with the same internal signal. The internal signal is supposed to be shifted due to electronic delays \( \Delta t_{int} \).

\[
y_{RTS}^{(BB, delay)} \cdot \left[C_{int} \cdot \cos\left(\omega_{RTS} \cdot \left(t - \Delta t_{int}\right) + \varphi_{RTS}\right)\right] = \frac{C_{RX} C_{int}^2}{4} \cdot \ldots
\]

\[
\left[\cos\left(\frac{\omega_{RuT}}{2} \cdot \left(t - T_{Delay} - \frac{R_{meas}}{c_0}\right) + \omega_{RTS} \cdot \left(T_{Delay} - \Delta t_{int}\right) + \varphi_0\right) \ldots
\right.
\]

\[
\left. + \cos\left(\frac{\omega_{RTS}}{2} \cdot \left(t - T_{Delay} - \frac{R_{meas}}{c_0}\right) + 2 \varphi_{RTS} - \varphi_0\right)\right]
\]

It is obvious that the right frequency point has the original receive frequency which can be represented as

\[
\omega_{RuT} = \omega_{RTS} + \Delta \omega \rightarrow \Delta \omega = \omega_{RuT} - \omega_{RTS}
\]

The frequency of the left frequency point is

\[
\omega_{left} = 2 \cdot \omega_{RTS} - \omega_{RuT} = \omega_{RTS} - \Delta \omega
\]

which is the mirror frequency of \( \omega_{RuT} \) mirrored at \( \omega_{RTS} \). If the RaTaSim source frequency is located out of the band (mostly below the band, e.g. at 23.8 GHz) and \( \omega_{RuT} \) is located within the band the mirror frequency will be below \( \omega_{RTS} \) and located out of the band, too.

It is possible to transmit the complete frequency composition towards the RuT. When mixing down the left frequency point in the radar system a difference frequency of approximately 2\( \Delta \omega \) is occurring (in our example at least 400 MHz) which will be filtered out by the RuT. In [4] it is proposed to filter out the mirror frequency. Thus, it is important to keep a certain offset between the internal RaTaSim frequency and the lower edge of the frequency band. When using narrowband patch arrays the left-side frequency point is filtered out by the antenna itself. For the further development we neglect this frequency component. The upconverted signal is again transmitted by the TX antenna of the RaTaSim and received by the RuT, the delay time \( T_{Delay} \) can be represented as an equivalent distance \( \Delta R \).

\[
y_{RTS}^{(RX)} = B_{sim} \cdot \cos\left(\omega_{RuT} \cdot \left(t - 2 \cdot \frac{R_{sim}}{c_0} + \Delta R + \frac{R_{meas}}{c_0}\right) + \ldots
\]

\[
\omega_{RTS} \cdot \left(T_{Delay} - \Delta t_{int}\right) + \varphi_0
\]

\[
\left(10\right)
\]
Mixing down in the RuT yields the following signal

\[ y_{RuT}^{(BB)} = C_{sim} \cdot \cos \left( \frac{2\omega_{RuT}}{c_0} R_{sim} + \omega_{RTS} \cdot (T_{Delay} - \Delta t_{int}) \right) \]  

(11)

Compared to the base-band signal of a real target described in eq. 4 the simulated distance \( R_{sim} \) corresponds to the real target’s distance \( R_{Target} \). But in addition there is a phase error \( \omega_{RTS} \cdot (T_{Delay} - \Delta t_{int}) \). The second part \( \omega_{RTS} \cdot \Delta t_{int} \) is not changing when \( \omega_{RTS} \) is constant. The constant phase can be interpreted as a phase shift at the reflection plane of a target. In the case of changing \( \omega_{RTS} \) a variable error is occuring. Furthermore the first part \( \omega_{RTS} \cdot T_{Delay} \) is including an addition constant phase error when both factors are constant. When \( T_{Delay} \) is changing which is important for dynamic simulations a erroneous Doppler shift is occuring in addition to the real Doppler with \( \Delta R = v \cdot t \)

\[ \omega_{D} = \frac{2\omega_{RuT}}{c_0} v + \frac{2\omega_{RTS}}{c_0} v \]  

(12)

It can be suggested that this erroneous Doppler can be compensated when changing \( \omega_{RTS} \) in the manner that with changing \( \Delta t \) the phase error stays constant. This method has limitations. On the one side the RaTaSim signal source is limited in frequency range and furthermore a simulation of multiple targets will not possible when adjusting \( \omega_{RTS} \) for one target. Thus the radar target simulation with out of band source is limited and simulations allowing Range-Doppler processing in the RuT are not possible.

### 2.2 Radar Target Simulator with in-the-band source

It will be supposed that the RaTaSim source frequency is located in the middle of the band of interest (e.g. at 24.125 GHz for the ISM band). The formulas as derived in the subsection before can still be used. But due to the location of \( \omega_{RTS} \) exactly in the middle of the band the mirror frequency (formerly known as \( \omega_{LRf} \)) is located in the band, too. It will be filtered out when the distance between both frequencies is higher than the output low-pass frequency of the RuT. Nevertheless disturbances are arising when both frequencies are close together which will occur in each frequency ramp. It can be supposed that with the actual setup radar target simulation is not possible. The setup needs to be modified: Single-side band mixers for down- and up-conversion are used. Due to these mixers two signals are available in the base-band, the in-phase (I) and the quadrature (Q) signal.

\[ y_{RTS}^{(Q, delay)} = -\frac{C_{RX} \cdot C_{int}}{2} \sin \left( \left( \omega_{RuT} - \omega_{RTS} \right) \cdot \left( t - T_{Delay} \right) + \frac{R_{meas}}{c_0} \phi_0 - \phi_{RTS} \right) \]  

(13)

The Q-signal is shifted by 90° to the I-signal. Mixing this signal not with eq. 5 but with a signal shifted by 90° yields a RF signal which is quite similar to eq. 7 except the mirror frequency shifted by 180°. Thus when adding both signal only the original frequency component \( \omega_{RuT} \) is remaining.

\[ y_{RTS}^{(BB, delay)} \cdot C_{int} \cdot \cos \left( \omega_{RTS} \cdot \left( t - \Delta t_{int} \right) + \varphi_{RTS} \right) + \ldots \]  

\[ y_{RTS}^{(Q, delay)} \cdot C_{int} \cdot \sin \left( \omega_{RTS} \cdot \left( t - \Delta t_{int} \right) + \varphi_{RTS} \right) = \ldots \]

\[ \frac{C_{RX} \cdot C_{int}^2}{2} \left[ + \cos \left( \omega_{RuT} \cdot \left( t - T_{Delay} - \frac{R_{meas}}{c_0} \right) + \ldots \right) \right] \]  

right frequency point

\[ \omega_{RTS} \cdot (T_{Delay} - \Delta t_{int}) + \phi_0 \]  

(14)

#### 2.2.1 Description of mixture process in complex domain

The complete mixture process can now be considered in the complex domain. The real RaTaSim receive signal \( y_{RTS}^{(RX)}(t) \) (eq. 6) can be described in complex form

\[ y_{RTS}^{(RX)}(t) = \frac{C_{RX}}{2} \left( e^{j\left( \omega_{RuT} \cdot \left( t - \frac{R_{meas}}{c_0} \right) + \varphi_{RuT} \right)} + \ldots \right) \]  

\[ e^{-j\left( \omega_{RuT} \cdot \left( t - \frac{R_{meas}}{c_0} \right) + \varphi_{RuT} \right)} \]  

(15)

Mixing eq.15 with the complex internal signal (compare eq. 5)

\[ y_{RTS}^{(int)}(t) = C_{int} e^{j(\omega_{RTS} \cdot t + \varphi_{RTS})} \]  

(16)

allows to distinguish the I-channel by the real part and the Q-channel by the imaginary part.

\[ y_{RTS}^{(BB)} = \frac{C_{RX} C_{int}}{2} \left[ e^{j(\omega_{RuT} + \omega_{RTS} \cdot t - \omega_{RuT} \cdot \frac{R_{meas}}{c_0} + \varphi_{RuT} + \varphi_{RTS})} \right. \]

\[ \ldots + e^{j(\omega_{RuT} + \omega_{RTS} \cdot t + \omega_{RuT} \cdot \frac{R_{meas}}{c_0} - \varphi_{RuT} + \varphi_{RTS})} \]  

(17)

Mixing up with the conjugate-complex internal RaTaSim signal (but with negative sign in the exponential function)

\[ y_{RTS}^{(int)}(t) = C_{int} e^{-j(\omega_{RTS} \cdot t + \varphi_{RTS})} \]  

(18)

allows the reconstruction of the original receive signal by the real part

\[ y_{RTS}^{(TX)} = \frac{y_{RTS}^{(int)}}{2} \cdot C_{int} e^{-j(\omega_{RTS} \cdot t + \varphi_{RTS})} \]  

\[ = \frac{C_{RX} C_{int}^2}{2} e^{j(\omega_{RuT} + \omega_{RuT} \cdot \frac{R_{meas}}{c_0} - \varphi_0)} \]  

(19)

which is the same equation as equation 14 neglecting the artificial delay and an internal electronic time delay. It will be supposed that the complex signal is delayed by \( T_{Delay} \) which yields a phase shift over frequency in the complex domain. The
complete mixing process including this additional delay can be described as

$$y^{(TX)}_{RTS}(t) = \begin{pmatrix} y^{(RX)}_{RTS}(t) \cdot e^{j\omega_{RTS} T_{Delay}} \cdot e^{-j\omega_{RTS} T_{Delay}} \\ \end{pmatrix}$$

where the receive signal is directly represented as complex signal (in order to neglect the filtering in the calculation)

$$y^{(RX)}_{RTS}(t) = C_{RX} \cdot e^{j(\omega_{RTS} (t - \frac{Rmax}{c}) + \phi)}$$

As the delay will later be implemented in the baseband the delay term needs to be separated into two terms.

$$e^{-j\omega_{RTS} T_{Delay}} = e^{j(\omega_{RTS} - \omega_{RTS} T_{Delay})} \cdot e^{-j\omega_{RTS} T_{Delay}}$$

The complex signal is delayed by the time $T_{Delay}$. The two physical signals $I$ and $Q$ can be interpreted as complex signal but with additional phase shift.

$$y'_{Delay} = y'^I_{Delay} - jy'^Q_{Delay}$$

This derivation shows that in order to delay the radar signal in the RF domain without an additional phase shift as it occurs by mixing down with a double side band mixer (as in section 2.1) the complex signal must be multiplicated with $e^{-j\omega_{RTS} T_{Delay}}$ in order to suppress the additional phase shift. Thus the usage of an I/Q mixer for radar target simulation is one of the major advantages. This yields for the real signals $y'^I/Q_{Delay}$ which are upconverted:

$$y'^I_{Delay} = y'_{Delay} \cdot \cos(\omega_{RTS} T_{Delay}) - y'^Q_{Delay} \cdot \sin(\omega_{RTS} T_{Delay})$$

$$y'^Q_{Delay} = y'_{Delay} \cdot \sin(\omega_{RTS} T_{Delay}) + y'^Q_{Delay} \cdot \cos(\omega_{RTS} T_{Delay})$$

Furthermore an in-the-band source has the advantage of dividing the band into two parts of same bandwidth size. In the baseband channels only signals from $-\Delta f/2$ up to $+\Delta f/2$ (with $\Delta f$ being the bandwidth) are arising. This allows lower sampling rates for analog-digital-conversion.

3 State-of-the-art

There are already existing solutions for radar target simulation:

1. Smart Microwave Sensors GmbH, SMS KTSDG-02 [5]: A system which mixes down a 24 GHz receive signal to an intermediate frequency (IF) at 6.5 GHz. For radar systems operating at 77 GHz a additional converter is necessary. The IF-signal can be delayed by a coaxial cable or again be mixed-up into the optical regime and transferred over a optical fiber. The simulator only allows to simulate one single target which has a constant range. The Doppler effect is modeled by a separate oscillator which models the doppler shift. A target provoking a Doppler shift but which is not changing the range is non-physical.

2. PERISENS [4]: A comparable system to the one above. The signal is mixed-down to an unknown IF frequency and delayed in the optical domain. The lines can be switched thus a non-static target can be simulated. The target changes non-continuously its range in steps of 30 cm. The simulator can simulate several targets by splitting the power and transferring them over different lines. A Doppler shift is generated by an offset in the up-converter LO.

3. RFBEAM Radar Doppler Target K-FT1 [6]: A out-of-the-band RaTaSim system with an internal LO source at 23.8 GHz. The delay is realized by a FPGA processor. The system is still in development.

4. Rohde&Swarz ARTS9510 Automotive Radar Simulator [7]: A high-class test system based on RF measurement technology by miro-sys operating in the 75 up to 82 GHz range with a bandwidth of up to 1000 MHz. The minimum range can be chosen down to 6 m depending on the bandwidth (400, 500 and 1000 MHz). For each configuration 4 simultaneous targets can be simulated. The range increment is 60 down to 24 cm (depending on the bandwidth). The Doppler

5. AGILENT E8707A Radar Target Simulator [8]: A radar target simulator based on Keysight measurement technology which could simulate up to 2 targets only for static scenarios over a bandwidth of 1 GHz in the 76-77 GHz band. The Doppler shift is simulated by an additional mixed-signal generator which is connected to the the Radar target simulator and which shift the transmit frequency by an additional frequency. The system needs an external 10 MHz reference, the Doppler seems to be realized by an additional Doppler oscillator.

6. ANRITSU Radar Test System ME7220A [9]: A radar test system from early days which has been discontinued. This system was only able to simulate one single target. The step size for targets in the near range were 0.5m.

7. National Instruments (NI) TS10105 [10]: A radar target simulator based on RF measurement technology from NI and Konrad Technologies embedded in the typical NI test and simulation environment. Depending on the RF components the system operates in the 24 or 79 GHz automotive range.

4 Proposal for low-cost solution

The simulators in the subsection before are mostly not low-cost. Especially the simulators from dedicated manufactur-
ers of RF-measurement technologies (R&S[7], Keysight[8], ANRITSU[9] and National Instruments[10]) are based on their RF-measurement technology which is of high cost (starting from several 100kEuro). The simulators coming from other manufacturers ([4],[5],[6]) have non-variable ranges for only one single target or dynamic ranges with high step sizes for few targets. For the latter the targets are “jumping” in the range domain, while the Doppler is simulated by an additional Doppler shift which is not physical. In this section a radar target simulator with an in-the-band-source is presented[12]. Due to the low frequency of the baseband signals these can be digitized and delayed in a logic unit. Figure 3 shows the complete schematic of the radar target simulator.

Two orthogonal polarisations of the RuT are processed in parallel. This allows the considerations of all polarisation types (linearly and circularly polarized). In contrast to the most RaTaSim systems on the market the antennas should be realized in patch antenna technology with high isolation between RX and TX channel instead of expensive horn antennas. All semiconductor components (e.g. I/Q mixers, VCO, LNA, PLL, etc.) are based on radar technology from known semiconductor manufacturers producing in the radar frequency range. The delay is realized by a “virtual” transmission line in a FPGA which allows low-latency processing of the digital data. The analog-digital conversion must be of high sampling rates, of high resolution and of low-latency, too. The additional inaccurate Doppler shift which is caused by the delay in the base band can be corrected in the FPGA due to the representation of the wave as complex value. The step-size of the radar targets will be in the sub-mm range which allows the inherent the modeling of the Doppler effect which has been shown in [11].

5 Conclusion

In this paper the theoretical foundations of radar target simulations are given in a mathematical way with the focus on double- and single-side-band mixers. Internal signals which are lying inside and outside of the band of interest are investigated. A concept for the correct Doppler simulation for I/Q mixer topologies is presented. An overview of actual state-of-the-art system is given. In the end a low cost system for radar target simulation is presented which is in development actually.

References


[5] Smart Microwave Sensors, KTSDK-02

[6] RFbeam, K-FT1 Radar Doppler Target


