Radar Simulator's Signal Processing in the Distance Range down to the Zero Value

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Abstract. The paper considers devices designed to simulate a time-frequency structure of a radar signal reflected from a target or underlying surface. Proposed simulator can be used to simulate false radar targets including those located closer than the minimal delay the devices may implement in conventional simulators. An effective way is suggested to reduce the simulated range. The method works by real time application of an additional frequency shift. It may be useful to simulate the combat operation of a radar system, as well as to simulate echo signals of radio altimeters when probing by signals with various types of linear frequency modulation. The dynamic modification of simulating parameters is carried out in accordance with parameters of the input emitted signal.

Keywords: Altimeter, radar target, radar echo simulator, linear frequency modulation, digital signal processing

1 Introduction

A device for simulating a false radar target is intended to simulate the time-frequency structure of a radar signal reflected from an underlying surface or from one or more targets located in a fixed direction. It can be used to simulate the following echoes from false target including those located closer to the carrier, and from underlying surfaces for radio altimeters (flight altitude meters).

Simulators may be useful to verify and even try to deceive the combat operation of radar systems in different circumstances [1, 5].

Here, radar systems, which operate with linear frequency modulated continuous waves (FMCW) are discussed, because they are widely used in manned and unmanned aircrafts and helicopters especially at low distances and altitudes. Their signals are convenient to effective processing with low level of emitted power [6, 12].

In order to qualitatively simulate the frequency-time structure of the reflected radar signals, we can use methods to form the reflected signal as a sum of signals reflected by number of different small flat facets (areas) of the surface; such facets are sufficiently smaller in comparison with the irradiated area. Facets may be equivalent to bright points in some target and surface models. Such approach is applicable and correct if their reflection coefficients are related to their physical areas, orientations, and local surface "brightnesses", *i.e.*, the radar cross section corresponds to the carrier wavelengths.

2 Typical simulator implementation with a delay line

A typical device for simulating radar targets with high resolution [1, 5] is shown in Fig. 1. The emitted pulse from the radar, for which a radar portrait is created, passes through the receiving (intercept) antenna, amplifier, bulk coarse delay unit, accurate delay unit, set of modulators, and adder to the output of the simulator. The bulk delay unit performs a time delay corresponding to the distance to the nearest bright point of a simulated target. A delay line with taps provides simulation of set of the bright target points. Amplitude and phase modulations are performed by using external reference signals U_i, which corresponds to the targets characteristics. From the output of the modulator, signals simulating the corresponding bright points are directed to the adder and then to the transmitting (retransmitting) simulator antenna.

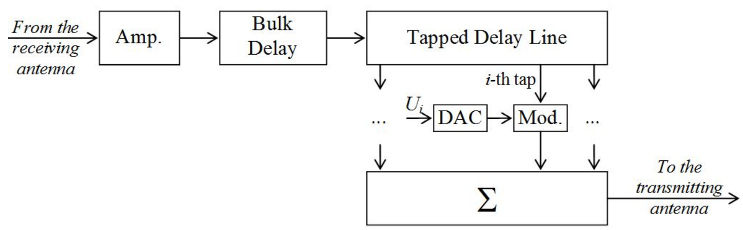

Fig. 1. Scheme of the high resolution simulator based on a tapped delay line

There exist many similar devices. The described architecture corresponds to the device for simulating real-world radar portraits [1] because of its structure and operation principle; see, for example, the “Radio frequency signature augmentation system” [2], the “Electromagnetic target generator” [3], the “Method for deceiving a sonar or radar detector, and a decoy for implementing the method” [4], and the “Method of augmentation of radar techniques” [5].

In practical application of the described methods and devices to simulating radar portraits with variable modulation parameters, the significant problem arises in simulating targets with ranges shorter than the distance to the carrier (or vehicle) that needs to be protected (hided) from the operating radar.

The same difficulties appear when we use signal simulators to study the characteristics of radio altimeters in seminatural modeling of work in a laboratory. It is impossible to simulate a signal with a signal propagation delay smaller than the intrinsic delay caused by transition time in processing channels and waveguides.

Now, the minimum delay is 40 nsec even in the best known schemes of digital signal memory (DSM), which corresponds to the range of 6 m. With the use of amplifiers, filters, attenuators, and connecting cables in real simulators, the corresponding minimum simulated range is 14–60 m and more. It limits both the ability to hide the real position of the carrier protected from the high-resolution radar and the ability to simulate low altitudes when testing radio altimeters.

It is known that both the Doppler shift and the time delay of the signal, which has a linear frequency modulation (FM) or an asymmetric sawtooth modulation, can be simulated by a corresponding offset of its carrier frequency [10, 11].

Therefore, to reduce the minimum simulated height and compensate its own delay in every hardware implementation, it is possible to use a certain frequency shift. For example, an FMCW altimeter with an up-chirp sawtooth modulation will register an equivalent low altitude if during the signal generation the additional frequency shift Δf is applied to the direction, which is approaching the transmitted $f_{tx}(t)$ and received $f_{rx}(t)$ signals in the analysis window (measuring part of the signal inside each repetition interval). See Fig. 2 where the $f_{rx}(t)$ graph is upshifted in the direction to be close to the $f_{tx}(t)$ graph.

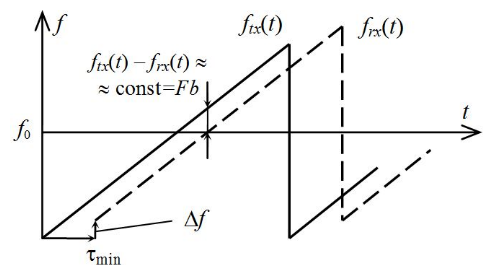

Fig. 2. Simulation of an equivalent lower altitude for up-chirp FMCW altimeters

Frequency of the heterodyning signal (so-called beat signal) at the output of the mixer in FMCW device is the difference between the frequencies of the following two signals:

$$f(t) = |f_{tx}(t) - f_{rx}(t)| \simeq \; const = Fb \tag{1}$$

where Fb is the value of the beat frequency of the signal at the altimeter mixers output inside the analysis window excluding the transition windows (the beginning-and-ending periodical areas of modulation frequency jumps in $f_{tx}(t)$ and $f_{rx}(t)$ graphs).

It is seen (Fig. 2) that the positive frequency shift Δf for the signal delayed by some minimum delay $\tau_{\min}$ will lead to a decrease in the average beat frequency Fb and, as a result, to a decrease in the measured altitude or distance.

The first disadvantage of this method is the dependence of the required sign of the frequency shift Δf on the direction (type) of the linear ramp fashion slope in up-chirp or down-chirp of the FMCW radar.

The second disadvantage is since the triangular wave modulation in the FMCW, which is the most widely used scheme [12]. Consider the case when we use only the positive frequency offset for the signal $f_{rx1}(t)$ signal (delayed by $\tau_{\min}$ and shifted upward by Δf relative to the signal $f_{tx}(t)$) in the both half-periods of the analysis windows (excluding the transition windows). Here, two values of the beat frequencies are formed: the $Fb_{\min}$ value in one half-period and the $Fb_{\max}$ value in the second half-period as by the $f_{rx1}(t)$ graph in Fig. 3

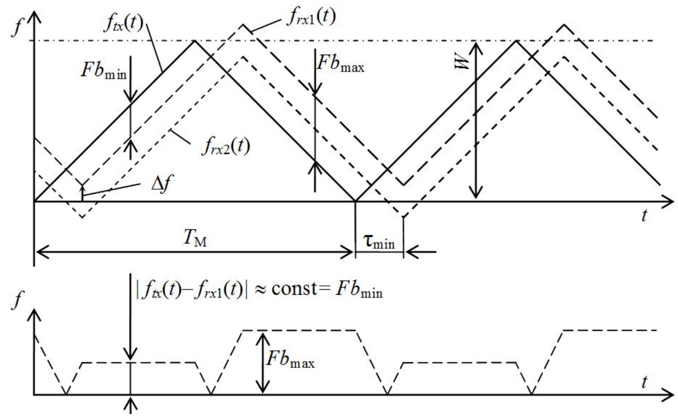

Fig. 3. Simulation of the lower altitudes in FMCW altimeters with the triangular modulation

If the measurement unit of such radar operates on the leading edge of the spectrum, then the problem of reducing the measured range could be solved. But, let in the example of a typical FMCW device a radar system uses a range measurement unit for the beat frequency corresponding to the "center of gravity" of the spectrum averaged over the whole repetition interval [12]. Then such a bifurcation of the original spectrum harmonics will not affect desirably the measured distance in the radar system.

The simple replacement of "$+\Delta f$" by "$-\Delta f$" will only lead to a change in the sequence of half-cycles with Fb_{min} and Fb_{max}, see the $f_{rx2}(t)$ in Fig. 3.

3 Sum of two frequency-shifted copies of the emitted signal

For mentioned cases, it is suggested to generate a reflected signal as the sum of two frequency-shifted copies of the emitted signal [7], see Fig. 4. It is effective for FMCW and long pulse signals with linear FM when the measured frequency shift is used to evaluate and accurately specify of the distance to the radar target.

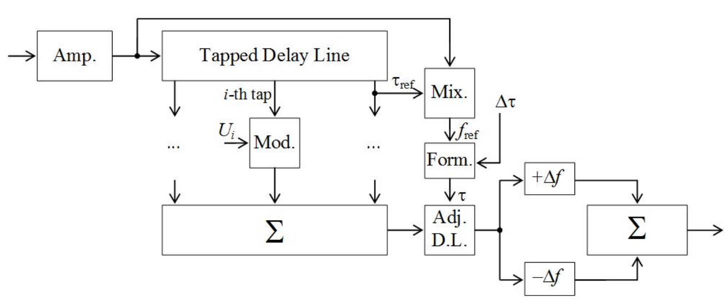

Fig. 4. Simulation of lower altitudes for triangular modulation FMCW altimeters

The frequency offset is performed of the same value Δf, but with opposite signs: "$+\Delta f$" and "$-\Delta f$". Here, Δf is the parameter selected approximately equal to or larger than the selective locking/tracking filter in the radar receiver.

The simulator comprises a mixer and a delay forming unit. The f_{ref} is the frequency formed at the output of the mixer. With its help, the value of the rate of change of the modulation frequency ($V_f = 2W/T_M$, where W is the modulation bandwidth and T_M is the repetition interval, Fig. 3) can be evaluated in the delay forming device.

Further, a delay value τ for the adjustable delay line is calculated by using also the desired offset of the delay "$\Delta\tau$" coming from the external device

$$\tau = \Delta\tau + \Delta f/V_f - \tau_{\mathrm{min}} = \Delta\tau + \Delta f\frac{\tau_{\mathrm{ref}}}{f_{\mathrm{ref}}} - \tau_{\mathrm{min}}, \tag{2}$$

where τ_{min} is the own (internal) delay in the simulator circuits; Dτ is the required offset delay with decreasing the simulated range or compensating for its own delay (when the value has the minus sign); τ_{ref} is the value of the signal's taken delay from any convenient output of the multiple-tapped delay line (see Fig. 4).

So, the original signal in the adjustable delay line is delayed by the delay τ. In this case, the delay value τ determines the displacement of the entire portrait of the simulated target in the range to a smaller one (for $\tau < \Delta f/V_f$) or higher (for $\tau > \Delta f/V_f$). For example, when τ=0, the distance to the simulated target will be reduced by

$$\Delta R_{\mathrm{max}} = \frac{c\,\tau_{\mathrm{min}}}{2} = \frac{c\ \Delta f}{2\ V_f}, \tag{3}$$

where c is the speed of light.

The value of the parameter Δf is chosen approximately equal to or greater than the bandwidth of the selective capture and tracking filter in the radar (altitude in the altimeter). However, in compliance with the condition for the correct processing the received signal in the radar, $\Delta\tau_0 \ll T_M$ and, therefore, $\Delta f \ll T_M V_f$.

Thus by [7], the device in Fig. 4 allows simulating two identical targets regardless of the direction and signs combination of the rate of linear frequency change. In this case, the first target (main target) can be simulated at a range shorter than the range of the radar carrier. But the second target will be further in range and, with the appropriate choice of parameters, will not interfere with the correct tracking of the main target. The result achieved is the simulation of a target with a range greater or less than the range of the carrier both for analog and digital signal processing.

4 Commutation instead of summation

It is possible to modify the structure in order to improve the performance and simplify the hardware implementation of the radar portraits simulator [7] of Fig. 4 when probing by such signals with various types of the linear FM. To simplify the hardware implementation, instead of the second adder and the pair of frequency shifters, the only one controlled frequency shifter can be used. Moreover, only one sign of the frequency shift value Δf is sufficient for the simulator to work with both the triangular and asymmetric sawtooth modulated signals.

An example of decreasing the simulated range for the triangular FMCW is shown in Fig. 5. Here, we use the periodically changing the plus sign or the minus sign for a given frequency shift value Δf. So, the entire signal of the previously generated portrait of the simulated target takes the offset in its distance.

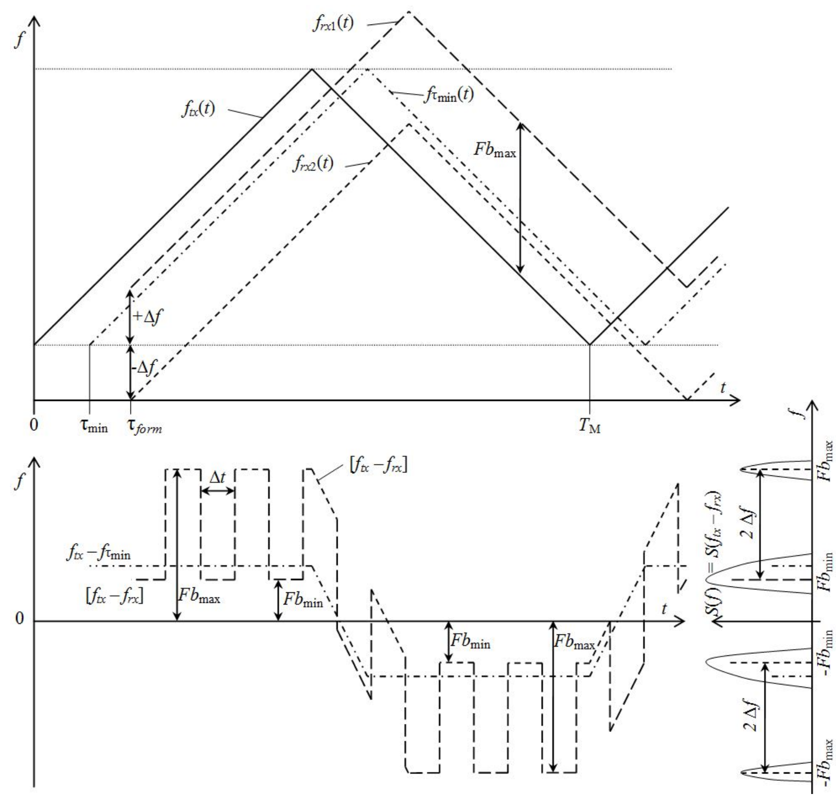

Fig. 5. Range harmonics and a beat signal spectrum while simulating the lower distance

Periodic change of the sign is carried out on regular intervals, and we denote this value Δt. Then, with continuous emission, the output signal will contain Δt length segments of the emitted signal with phase jumps at the instant of the sign change $\pm\Delta f$. In the frequency domain, this will result in harmonics corresponding to the sum, frequency differences of the "useful" signal, and to the sign changing frequency F_{sign} multiplied by an integer [8], where $F_{\text{sign}} = 1/(2\Delta t)$.

Let we select the F_{sign} (frequency of changing the sign) several times lower than the average carrier frequency f_0, but above the band of "useful" signal modulation frequencies (for example, at $\Delta t \ll T_M$) and take into account the actual presence of limiting frequency filters in all radar receivers. Under this the resulting signal in the working region will be equivalent by the spectral composition to the signal formed by the conventional summation of the signals, *i.e.*, as in Fig. 4.

The principle of replacement of signal summation by signal "commutation" was proposed and implemented in target simulators when probing with sufficiently long radiated signals [8]. In the case of FM signals, it is also true, because the spectral density of the radar probing signals with a chirp at each instant is concentrated in a narrow frequency band. So, if parameters of the simulator are chosen correctly, the interruption of the instant spectrum and the appearance of extra phase jumps will not affect the operation of typical radar. Under this, the target searching, locking, and tracking are performed without taking into account the phases of the signals with averaging into several resolution elements and, as a rule, in several repetition and scanning intervals.

Therefore, as a result of replacing the adder with the switchable modulator as in Fig. 4, we get a bifurcation of the spectra at each instant and in the first and second half-periods. Two pairs of spectral envelopes (for the point target those are only harmonics $Fb_{\min}$ and $Fb_{\max}$) in the general spectrum of $S(f)$ will be spaced along the frequency axis by $2\Delta f$, see Fig. 5. Thus, for the case of a FMCW radar with an arbitrary chirp slope, Δf is greater than the bandwidth of the bandpass (lowpass) beat signal filter. So, the high-frequency harmonics will be suppressed or discarded, because the "second simulated range" are far from the simulated target (surface). Moreover, and the real measured range value will correspond to the "center of gravity" of the low-frequency envelope of the spectrum with a smaller value of the "first simulated range" (altitude).

In Figure 5, the harmonic $f\tau_{\min}(t)$ are also shown for comparison. It corresponds to a signal with real minimum delay $\tau_{\min}$ with none of frequency shift. Its position in both half-periods of the modulation period is constant. So, it hits (Fig. 5) the tail part of the low-frequency envelope of the spectrum of the beat signal, *i.e.*, to the right of the harmonic $Fb_{\min}$ obtained by the proposed design of the simulator.

Thus, we simplify the hardware implementation of the simulator in Fig. 4 in the following way. Instead of the second adder and two frequency shifters, the sign switcher, one frequency shifter, and, also, additional adjustable amplifier are introduced. The device is shown in Fig. 6.

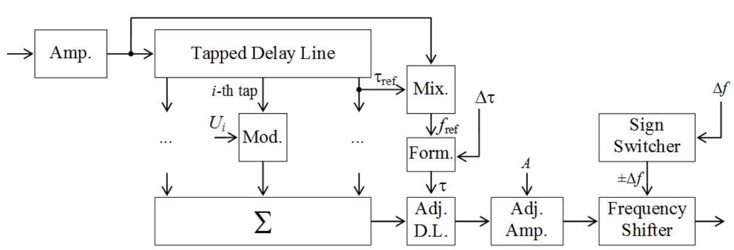

Fig. 6. Simulator with the switcher of the sign of the frequency shift

The simulator in Fig. 6 receives an emitted pulse from the radar, for which a radar portrait is created, by the receiving antenna through. Further there are the amplifier, multi-tapped delay line, set of modulators, adder, adjustable delay line, adjustable amplifier, and frequency shifter to the output of the simulator. The multi-tapped delay line provides simulation of bright points of the target(s) with individual delays. Individual amplitude and phase modulations are performed and they use the appropriate coefficients generated by the external device.

The output signal is obtained by shifting the frequency of the signal of the generated radar portrait of the target, and the frequency shift is performed alternately by the "$+\Delta f$" and "$-\Delta f$" units.

To implement this, the sign switcher is used. It inverts the frequency offset value through time-equal intervals Δt, *i.e.*, frequency of signal is changed at the output of the sign switcher $F_{\text{sign}} = 1/(2\Delta t)$. Let the value of F_{sign} be selected several times lower than the average carrier frequency f_0 and outside the band of the "useful" modulation frequencies of the radar signal; and let us take into account the actual presence of limiting signal filters in all radar receivers. So, the resulting signal in the working (usually low-frequency) region by the spectral composition will be equivalent to the signal formed by the usual summation of signals [8].

In the laboratory, as well as when working onboard with a low level of interference in the signal from the receiving antenna, it is possible to determine not only the absolute value of the rate of the linear frequency change but also the sign of that rate. This makes it possible to improve the quality characteristics by performing a frequency shift only in the desired direction. This means that harmonics corresponding to the second target will not be present in the output signal of such simulator.

To achieve this result, the simulator is supplemented with a chirps sign detector, whose input is fed from the amplifier (Fig. 7). The signal from the output of the chirps sign detector comes to an additional second input of the sign switcher of the frequency shift value; for example, this may be the value "±1", where "+1" must correspond to "$+\Delta f$" at the output of the sign switcher, and "–1", must match "$-\Delta f$" at the output of the sign switcher.

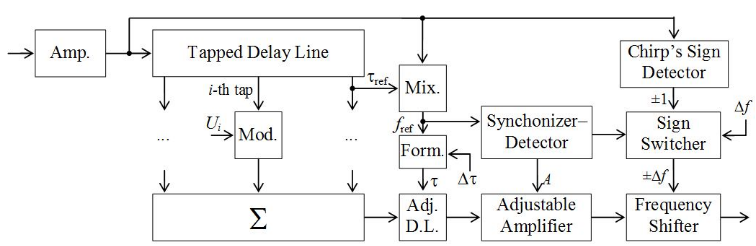

Fig. 7. Simulator with the switcher of a sign of the frequency shift

When working on board of an aircraft, the level of interference and the level of the useful signal can vary within wide limits. This can lead to an incorrect work of the chirps sign detector and of the sign switch controlling the frequency shifting device. Therefore, it is necessary to complete the measurement of the parameters of the chirp signal by estimating the power characteristics of the signal from the receiving antenna in order to adjust the parameters of the simulator. To provide this, the simulator is supplemented with a Synchonizer-Detector (see Fig. 7).

The Synchonizer-Detector evaluates characteristics of the signal converted into the mixer and sets the corresponding mode of operation of the simulator. For example, it is provided the following way. If the signal level is insufficient, the simulator mode is selected with periodic change of the modulation frequency shift sign with equal intervals Δt independently of the output signal of the linear FM detector, and a gain value is given to the adjustable amplifier, for example, in the range $A = 2...3$.

If the signal level is sufficient, the chirps sign detector must correctly monitor the sign of the frequency change of the chirp signal. Therefore, such a mode of operation of the simulator is established, in which the modulation frequency shift is determined by the output signal of the chirps sign detector; here the gain value is given to the adjustable amplifier, for example, in the range $A = 1...1,5$.

The control of the gain value A allows one to improve the energy characteristics depending on the mode of operation of the simulator by reducing the level of the emitted signal of the target simulation by a factor of 2 with a correct determination of the sign of the change in the frequency of the chirp of the input signal. If there is no input signal with given/expected parameters or there is an intermittent or pulse radar signal, the gain value $A = 0$ can be output to the adjustable amplifier; this further improves the power characteristics.

To implement a delay line simulator device, modulators and adders can be analog or digital. To improve the quality of simulation, the signal generation is better to perform digitally on digital delay lines and modulators.

In [14], an example of the structure of a radar target simulator is given. The structure provides formation of an equivalent sum of signals spaced along the range of long-range target (or surface) elements. The unit uses the MC2301 PCI digital-signal memory-evaluation board based on the System-on-a-Chip 1879BM3 DSM developed by RC “Module” [13].

In accordance with [9] an additional amplifiers, attenuators, and possible mixers can be chosen to implement the radar target simulator. For example, suitable mixers, filters, and local oscillators should be used to downconvert the high carrier frequency into the frequency range of the signal processing units.

To exclude the output signal of the transmitting antenna from entering to the input of the receiving antenna, it is possible to use a circulator, strobe operation, and / or spatial diversity of the antennas [1]. In stationary tests, it is possible to connect cables directly to the radar system, that was investigated without use of the antennas.

5 Conclusions

Peculiarity of the described solution for simulator constructing is that regardless of the magnitude, direction, and combination of the signs of the rate of sawtooth frequency change, two identical false radar targets are simulated. The first one is the main target. It can be simulated at a range shorter than the range of the radar carrier. The second target is assigned in range by $2\Delta R_{\max}$, and with the appropriate choice of the value of Δf, this will not interfere with the correct tracking for the main false radar target.

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