Numerical Modeling of Feed Through Signal Rejection in FMCW GPR

Alexey A. Kalmykov, Kirill D. Shaidurov
Ural Federal University
Yekaterinburg, Russia, 620004
k.d.shaidurov@ieee.org

Abstract

FMCW georadar feed through signal rejection is simulated. A functional model is built with the help of AWR VSS design environment including MATLAB digital processing insertion. Designed model is mostly parameterized which makes it possible to bring the model closer to reality. The process of large feed through signal rejection, including modulating, demodulating and direct coupling signal frequency estimating is shown. The real ADC dynamic range increased to 25÷30 dB or 4-5 bit resolution is reached.

1 Introduction

Subsurface radar is to obtain the information about objects and layers in concealed environments by irradiating the area investigated with electromagnetic waves and recording reflected signals. Fundamentally two basic schemes for constructing a subsurface radar are possible. There can be either impulse georadar or a radar with continuous emission. Each scheme has its fundamental advantages and disadvantages. One of the main disadvantages of a continuous wave GPR is a feed through signal, or a parasitic antenna-to-antenna coupling. With minimal attenuation, this signal has a power that is several orders of magnitude higher than the power of reflections even from the upper layers of the soil. This problem is especially topical when considering the VHF band radar (strong coupling of small-size antennas), especially those working in a "raised" position above the ground.

From the experiments with the VHF band's GPR radar, the authors found that the reflection power from a well-conducting object at a short range is approximately 25÷30 dB less than that of the inter-antenna communication signal. Having a 16-bit ADC and adjusting the IF amplifier by the level of inter-antenna communication, we inefficiently use the DD section of the ADC, digitizing 25÷30 dB of the "unnecessary" feedthrough signal. Based on an approximate estimate of 6.02 dB / bit, the bit loss is 4÷5 bits leading to A decrease in the level of SINAD with further "pulling" of useful signals in a digital form.

One of the solutions to this problem is presented in [1]. According to one of the authors of this work, this scheme has a number of disadvantages that do not allow its use in a VHF georadar with a mobile synthesized aperture [2]. The authors suggest a different version of parasitic light signal elimination, originating in the publication [3]. This work is performed in the MATLAB environment and shows the principal possibility of the algorithm functioning. The purpose of this work is to deepen the study of this possibility of constructing a scheme for suppressing the signal of inter-antenna communication. The task is to move from the mathematical model of the algorithm (MATLAB) to the functional model (AWR VSS + MATLAB). This allows you to specify many parameters of elements and nodes and thereby bring the model closer to reality.

2 Model Description

The model of the proposed signal processing scheme for the chirp signal was constructed in the AWR VSS design system at the functional level. This system allows radio frequency nodes and devices with analysis of frequency, noise, statistical and many other properties and parameters to be simulated. To realize the stage of digital processing, the MATLAB package is used. It is called in the process of real-time operation of the model.

The scheme modelled was divided into separate modules in order to increase the flexibility of customization and simplify the visual perception in the working space of the design system. Below are only diagrams of the most important nodes of the model due to the general awkwardness. The general scheme is shown in Fig.1. Here are the following blocks:

– S_1 "transmitted" block – the DDS, forming the chirp signal $\{ F_N + f_{LZ}, F_V + f_{LZ} \}$, sent to the transmitting antenna. The modulating function of this DDS contains the additive f_{LZ} , which acts as a delay line in the transmitter path.

– Block A_1 is the signal propagation channel in a free environment. Contains three S_i channels, each of which is characterized by relative attenuation and frequency shift: S_0 (0 dB, 0.4 MHz), S_1 (25dB, 1.07 MHz), S_2 (35 dB, 1.53 MHz), where S0 is the inter-antenna link, S_1 and S_2 are the channels of reflected signals.

– S_2 block "basic_LO" – the DDS, which forms the reference chirp signal $\{F_n,F_v\}$. The circuit of the block is similar to the circuit of block S1, the difference consists in the absence of a shift of the modulating function f_{LZ}, which simulates the delay line. If it is necessary to reduce the amount of DDS in the circuit, the blocks S_1 and S_2 merge into one and a classical scheme with a power divider and a delay line in the form of a cable section is implemented.

– S_3 block "IF_loop" -the channel for estimating the frequency of inter-antenna communication. The block diagram is shown in Fig.2. The mixture of beat signals and the inter-antenna communication signal after conversion to the IF is filtered from the RF components by the filter F_1 and through the ADC falls into the sub-block A9 "MATLAB". In this sub-block, the work of the DSP, which computes the DFT and simulates the frequency of the inter-antenna communication signal over the maximum of the amplitude spectrum, is simulated. Further, this estimate is converted into units of the DDS phase battery control code, summed with the "reference" simulation function and fed to the second / third DDS input.

– S_4 "IF_signal" – the channel for estimating the frequencies of beat signals. This channel is "informational", the results of its digitization are the output signal of the LFM locator analog part. This unit consists of a low-pass filter F4 to eliminate the RF components after the mixer, block A10 "CHANGE_FS" to reduce the sampling frequency in order to simulate the signal in the VSS system more accurately, and the F7 bandpass filter, reflecting the inter-antenna communication signal at the frequency.

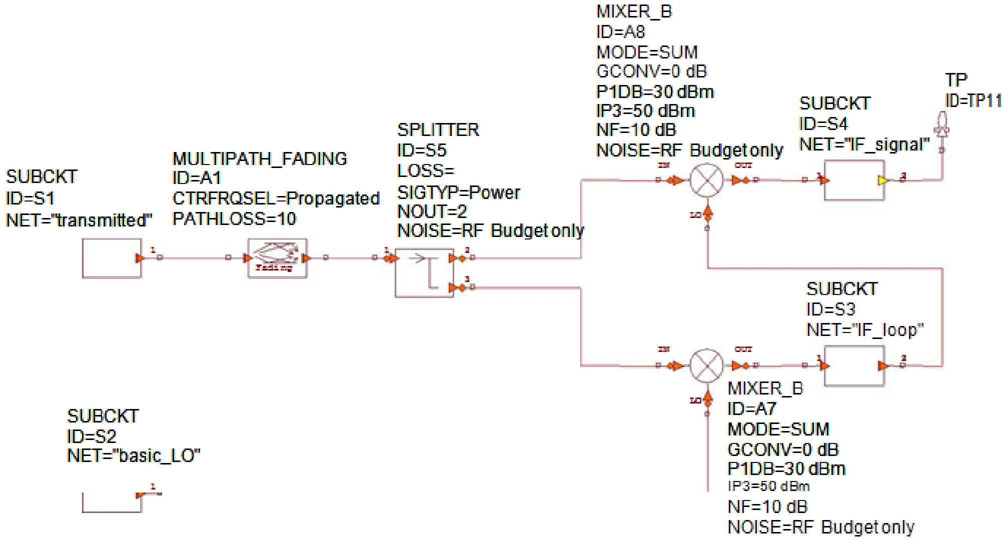

Figure 1: Functional model of feed through signal rejection scheme

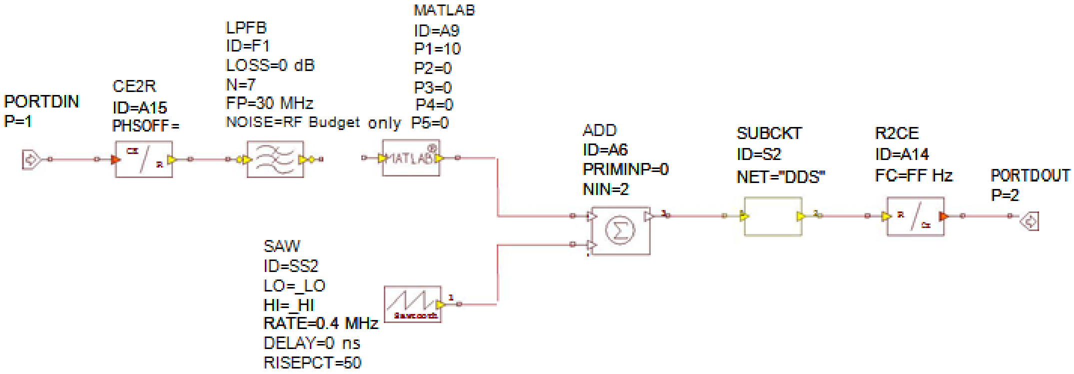

Figure 2: S3 "IF_loop" block diagram

– blocks A7 and A8 are mixers with the parameters corresponding to actually used mixers.

The logic of the scheme is as follows. The DDS of S_1 generates a chirp emitted signal, including the frequency correction fL3, equivalent to the presence of a delay line. In effect, the introduction of a constant delay line is equivalent to an increase in the intermediate frequency by the f_{LZ} amount that is necessary to increase the number of transitions through zero when analyzing sufficiently low-frequency beat signals. The generated chirp with the frequencies $\{F_N + f_{LZ}, F_V + f_{LZ}\}$ passes through the multichannel channel model propagation A1, in which it acquires frequency shift proportional to the distance delays f_0, f_1 and f_2, as well as relative attenuation.

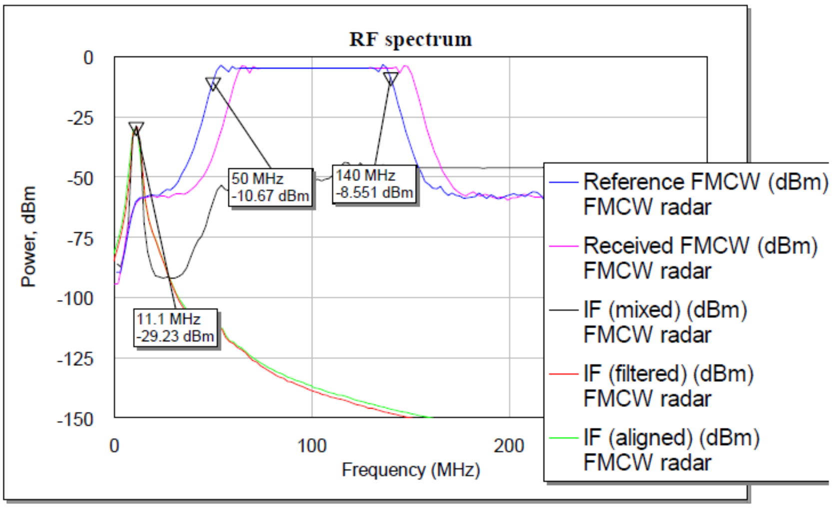

Figure 3: HF signal spectra before and after demodulation

Further, in the mixer A7, the signal received from the channel A_1 is demodulated by the reference chirp from the S_2 block, which does not form any delays ($\{F_N, F_V\}$). Thus, the frequency range of the beat signals spectrum, including $\{f_0, f_1, f_2\}$, turns to a nonzero IF f_{LZ}. At the same time, the inter-antenna communication signal, which appeared at the frequency $f_3 + f_0$, is much higher in level of power than the level of the reflection signals. In this case, the frequency f0 "walks" depending on the distance between the antennas.

The next step in the channel for estimating the frequency of inter-antenna communication is the filtration and digitization of a narrow band of beat frequencies. In this case, the IF amplifier is adjusted by the level of the inter-antenna communication signal, and the dynamic range of the ADC is used inefficiently from the point of view of processing low-power signals of reflections. The frequency of the inter-antenna communication is estimated with the help of a short-time

DFT (STFT) [3], then it is transferred to the control code of the DDS phase accumulator and added to the modulating function (the amplitudes of the modulating function and the additive code are summed up, since DDS is controlled by "ladder" Modulating function remains constant). A second reference chirp with frequencies $\{F_N + \widehat{f_0}, F_V + \widehat{f_0}\}$ is generated. At the last stage, the received and second reference signals are multiplied, as a result of which the inter-antenna communication signal is "centered" at the selected intermediate frequency f_{LZ}:

$$\widetilde{f_0} = (F_N + f_{LZ} + f_0) - (F_N + \widehat{f_0}) \approx f_{LZ} \quad (1)$$

At the same time, accordingly, all beat signals which are the area of our interest acquire frequencies:

$$\widetilde{f_l} \approx f_{LZ} + (f_i - \widehat{f_0}) \quad (2)$$

where f_i - the real frequency of the i-th reflection, $\widehat{f_0}$ - the estimate of the frequency of the inter-antenna communication, and $\widetilde{f_l}$ - the digitized frequency of the i-th reflection, taking into account the offset to the zero range with respect to the frequency of the inter-antenna communication.

3 Results of Modeling

We are to analyze the operation of the scheme step by step, moving from a high inter-antenna connection to a channel for estimating the beat frequency.

The following is worth noting. The measurement of any frequency signals, either RF or IF, occurs at the sampling frequency of the modeling system itself, that is, the frequency of the DDS (2 GHz) operation. Therefore, it is difficult to calculate and visualize the spectrum of low-frequency signals. To solve this problem, the sampling rate is reduced, the low-frequency signals are filtered and measured, and the Fourier spectrum is computed. These two cases correspond to the following two diagrams in Fig. 3 and Fig. 4, with a high and low sampling frequency, respectively. For the same reason, high-frequency diagrams "do not see" the individual frequency components of beat signals in the IF region (Fig. 3). Further, the simulation results, if necessary, the frequency to the intermediate frequency and from the frequency estimation channel are referred to immediately in two diagrams, implying the foregoing.

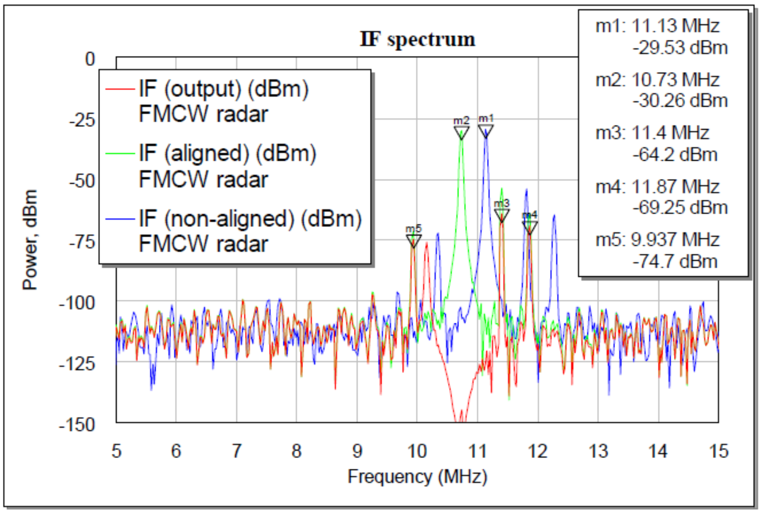

Figure 4: IF spectra of demodulated signals

3.1 High Frequency Channels (RF)

For modeling, three channels of radio waves {S_0, S_1, S_2} propagation with equivalent delay times of frequencies {0.4 MHz, 1.07 MHz, 1.53 MHz} and attenuation in the channel {0 dB, 25 dB, 35 dB} are given. Obviously, the first channel corresponds to parasitic inter-antenna communication, the second and third-signals of beats come from reflectors. The frequencies are intentionally selected by a multiple sampling frequency. Attenuation in the beat channels is equal to 25 dB and 35 dB based on the experiments with a chirp locator, which has showed the difference between parasitic illumination and reflection from a well conducting medium of at least 30 dB.

The modulation of the transmitted chirp has also an add-on f_{LZ} = 10.7 MHz, which is equivalent to shifting the range of useful signals to this IF. The frequency of 10.7 MHz is chosen as one of the standard frequencies for which high-quality surfactant filters and ceramic filters are manufactured, which allows narrowband filtering on the IF with a minimum of costs.

Taking into account the IF addition and delays in the propagation channel, the spectrum of the received chirp signal is shown in Fig. 3, the pink line. On the same graph, one can observe the spectrum of the reference chirp (blue line), which does not contain any frequency additives and used to demodulate the signal into the frequency estimation channel of inter-antenna communication.

The markers indicate the boundaries of the original chirp of 50 ... 140 MHz, obtained from DDS by analogy with the actual model of the LFM locator.

3.2 The Channel for Estimating the Frequency of Inter-Antenna Communication

For unexplained reasons, the DDS model used in the AWR VSS has an additive error of the phase code, and when a 10.7 MHz code is applied, the output has a frequency of 10.74 MHz, which will be taken into account below.

At the input of the channel mixer for estimating the frequency of inter-antenna communication, a reference "pure" chirp is received and the chirp received from the free space (channel A1). At the output of the mixer there are the results of frequency down conversion, as well as high-frequency products of multiplication of chirp signals, as shown in Fig. 3, a black line. After applying a low-pass filter with a band of 20 MHz, which eliminates all high-frequency components of the spectrum, we obtain a signal with the spectrum in Fig. 3, the red line. As was mentioned above, the IF spectrum in a narrow band is calculated after oversampling and is shown in Fig. 4, the blue line. The marker m1 denotes the maximum spectral component of the inter-antenna communication signal with a frequency of 11.13 MHz, which roughly corresponds to the expected frequency is $f_{\mathrm{LZ}} + f_0$ = 10.74 + 0.4 = 11.14 MHz. The following signal components have frequencies of 11.82 MHz and 12.28 MHz with the expected $f_{\mathrm{LZ}} + f_1$ = 10.74 + 1.07 = 11.81 MHz and $f_{\mathrm{LZ}} + f_2$ = 10.74 + 1.53 = 11.27 MHz. Further, the filtered mixture of signals at the IF frequency goes to the MATLAB block, which performs calculations in the MATLAB environment via the .m file. The frequency $\widehat{f}_0$ estimate is converted into a phase code and fed to the modulating function adder.

3.3 Beat Frequency Estimation Channel

An input "adaptive" chirp is received at the input of the mixer of the beat frequency estimation channel and received from the free space (channel A1) of the chirp. At the output of the mixer, the same mixture of beating signals for IF and high-frequency conversion products and forward signals is observed. After filtering the same LPF with a 20 MHz band, we get the spectrum shown in Fig. 3, the green line, and Fig. 4, the green line. Differences in the spectrum, of course, can be seen only on the "low-frequency" spectrum of Fig. Spectral peak of inter-antenna communication with a frequency of 10.73 MHz, marker m2 is observed. The expected frequency is + f0 - = 10.74 + 0.4 - 0.4 = 10.74 MHz. Thus, it can be concluded that the region of the spectrum containing beats and inter-antenna communication has shifted so that the frequency peak of the inter-antenna communication is established at the point 10.74 MHz (10.7 MHz at ideal DDS), which is taken as the zero range for further processing of beat signals.

The last stage is the filtering of the signal with a band-stop filter of the order 10 with the Chebyshev characteristic of type 1, whose central frequency is 10.7 MHz and deliberately does not adjust to the error frequency of the IF 10.74 MHz. The result of the filtration is shown in Fig. 4, the red line. It is seen that, despite the discrepancy, the spectral peak of the inter-antenna communication is suppressed to a considerable extent. Spectral peaks with frequencies of 11.4 MHz and 11.87 MHz (markers m3 and m4, respectively) are confidently distinguished. The expected frequencies

$$\widehat{f_1} \approx f_{LZ} + \left(f_1 - \widehat{f_0}\right) = 10.74 + (1.07 - 0.4) = 11.41\ MHz \quad (3)$$

$$\widehat{f_2} \approx f_{LZ} + \left(f_2 - \widehat{f_0}\right) = 10.74 + (1.53 - 0.4) = 11.87\ MHz \quad (3)$$

The power of the amplitude components of the beat spectrum is -64 dBm and -69 dBm, respectively (markers m3 and m4), whereas the power of the inter-antenna communication signal has decreased from -30 dBm (marker m1) to the noise level. Thus, attenuation of the useful signals was not more than 10 dB, while suppression of the forward parasitic signal was more than 100 dB. With this power ratio, the gain in the energy potential of the GPR receiver is obvious.

It is also possible to observe the component of the spectrum with a frequency of 9.937 MHz (marker m5), which is the product of the transformation in the beat frequency estimation channel, before the output of the circuit. This component can be filtered by both an analog filter and digital, and can simply not be taken into account when synthesizing 3D images as a frequency below the zero range (10.74 MHz), since it has a small amplitude and does not reduce AD DD.

4 Conclusion

As a brief discussion of the results, we give the following considerations. Functional modeling made it possible to carry out an experiment to suppress the parasitic signal of inter-antenna communication with a priori unknown frequency. The presented diagrams demonstrate the basic stages of signal demodulation, its processing, calculation of the inter-antenna communication signal frequency and repeated demodulation. The results of the model's work operation and the nested algorithm written in the MATLAB environment have confirmed the operability and allowed to reveal the bottlenecks of the proposed scheme.

An important feature of the scheme under consideration is the relative simplicity of implementing the prototype. In fact, the model is built from high-quality, but still easily accessible devices-ADCs, DDS mixers. All filters have constant parameters and can be realized on the basis of elements with lumped parameters. Transfer of the interfering forward run signal to a fixed frequency allows a simple and effective non-adjustable band-stop filter to be built.

The construction of a circuit from function blocks made it possible to flexibly specify a number of parameters of its nodes and modules, bringing the model closer to reality. For example, the use of a mixer in AWR VSS, unlike a simple multiplication operation in MATLAB in the demodulation stage, greatly enriches the spectrum with the products of the transformation, as can be seen from the spectra in Fig. At the same time, a number of parameters has remained untouched, the discussion of which we omit in view of the considerable volume of the required work. For example, the effect of noise, the dynamics of the MATLAB processing unit on the fluctuating frequency of parasitic light, and the time synchronization of the modulation periods of the reference and tunable DDS generators. Consideration of all these moments is the goal of the further work and the final stage of the digital simulation process of the scheme preceding prototyping.

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