Sounding Signals' Library for Reconfigurable Polarimetric FM-CW Radar – PARSAX

G. Babur, O. Krasnov, and A. Yarovoy

International Research Centre for Telecommunications and Radar, Delft University of Technology
2628 CD Delft, The Netherlands, Tel. +31-(0)15 27 86256, e-Mail: g.babur@tudelft.nl

Abstract

Diversity of sounding signal waveforms for polarimetric FM-CW radar is studied. Each signal represents a pair of mutually orthogonal wavelets which can be transmitted via two orthogonal polarizations. The signals compose a waveform library which has been implemented in the operational polarimetric software-defined radar PARSAX. This paper presents a sounding signals' library for polarimetric FM-CW radar. All the considered in this paper waveforms have been implemented in the operating polarimetric radar (in its FM-CW mode), namely in the PARSAX radar system developed in Delft, The Netherlands.

1. Introduction

Polarization, together with the amplitude, time, frequency, phase, and bearing descriptors of radar signals, completes the information which can be obtained on target returns in monostatic radars [1]. Polarimetric frequency-modulated continuous wave (FM-CW) radar uses pulse compression and provides polarimetric information with high resolution. A sounding signal for polarimetric radar consists of two signals transmitted on orthogonal polarizations, horizontal and vertical, for example. As far as polarization state of the signals can be changed during the process of scattering, as well as propagation, radiation and reception, the extra-orthogonality of sounding signals in addition to polarization one should be used. Additional orthogonality can be the orthogonality of waveforms. In this case, both orthogonally-polarized components of a sounding signal can occupy the same time interval and frequency bandwidth.

In this paper, we analyze pairs of mutually orthogonal wavelets with the same bandwidth and duration to be used in a polarimetric FM-CW radar. The pairs found are comprised in a probing signal library. The library is implemented into a software defined radar PARSAX, which serves as an experimental research platform for the waveform agility studies.

This paper is structured as follows. Section 2 contains the first part of the library presented by the most obvious pair of sounding signals, LFM-signals with opposite slopes, for polarimetric FM-CW radar. However, high level of cross correlation between such signals can result in the limited isolation of the radar receiver channels. Sections 3-5 introduce the other three parts of the library, which potentially can provide high level of isolation in the processing channels of polarimetric FM-CW radar. Some degrees of freedom within the presented library are described in Section 6, followed by the conclusion in Section 7.

2. LFM signals with opposite slopes

One of the most obvious pairs of orthogonal waveforms for polarimetric FM-CW radar is a pair of LFM signals with opposite slopes [2]. The complex envelope of such signals can be written as

$$\mathbf{u}(t) = \begin{bmatrix} u_H(t) \\ u_V(t) \end{bmatrix} = \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} \exp\left[j \cdot \pi \cdot k_0 \cdot (t - T/2)^2 \right], \\ \exp\left[-j \cdot \pi \cdot k_0 \cdot (t - T/2)^2 \right] \end{bmatrix}, \ 0 \le t < T, \tag{1}$$

where $u_H(t)$ and $u_V(t)$ are the signals transmitted on orthogonal (for, example, horizontal and vertical, subscripts H, V) polarizations. $u_1(t)$ and $u_2(t)$ are the up-going and down-going LFM signals defined along the sweep time interval T, $k_0 = \Delta F / T$ is the sweep rate of the LFM signals, ΔF is their bandwidth.

The continuous wave (CW) vector sounding signal for polarimetric FM-CW radar is

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$$\mathbf{u}_{CW}(t) = \sum_{n=-\infty}^{\infty} \mathbf{u}\left(t - n \cdot T\right), \tag{2}$$

where n is an integer.

The problem of use of LFM-signals with opposite slopes is their limited orthogonality. As far as the signals occupy the same time interval, the same bandwidth and have limited duration, they can not be completely orthogonal [3]. The cross-correlation between transmitted signals results in the limited isolation in the processing channels of the radar receiver, which can exceed the noise level significantly and mask the weak targets over the whole observed range. The presented further signals allow for solution of the problem of isolation defined by their cross-correlation.

3. Time-shifted LFM signals

One of the solutions of the isolation problem can be a pair of LFM signals having exactly the same shape, but a time shift relatively each other [4]. So, the second part of the library is presented by the time-shifted LFM signals:

$$\mathbf{u}(t) = \begin{bmatrix} u_H(t) \\ u_V(t) \end{bmatrix} = \begin{bmatrix} u_1(t) \\ u_1(t - t_{sh}) \end{bmatrix}, \quad 0 \le t < T, \tag{3}$$

where t_{sh} is a relative time shift between signals transmitted on orthogonal polarizations.

Using Eq. 3 in Eq. 2 yields the CW vector sounding signal transmitted on orthogonal polarizations. The signal transmitted with the horizontal polarization ($u_H(t)$) is a repetitive LFM-signal. The signal transmitted with the vertical polarization ($u_V(t)$) is the same repetitive LFM-signal but shifted in time on t_{sh}.

In case of de-ramping processing the time shift for LFM signals makes the appropriate frequency shift at every time instant, which can be identified as a *quasi orthogonality* in frequency domain. The corresponding signal processing technique is broadly consistent with the standard de-ramping processing in radar FM-CW receiver, but has some differences between some measured values (for example, between columns of the measured backscattering matrix) with the time shift t_{sh}. In practice the isolation in polarimetric radar channels for the time-shifted LFM signals is only limited by the amplitude-frequency responses of the low-pass filters (LPFs) used in the de-ramping filter in radar receiver. In the PARSAX radar system the achieved isolation was equal to 74dB for $t_{sh} = 0.4 \cdot T$.

The side-effect of the time-shifted LFM signals is the unambiguous range decrease at least twice [4]. The unambiguous range is determined not by the signals repetition T but by the time shift between the sounding signals $t_{sh} \le T/2$. It happens because the sounding signals have exactly the same form, are transmitted within the same bandwidth ΔF, the only difference is a relative time shift, which can be less or equal to half period.

4. Time-shifted LFM signals with extra coding

The solution of the unambiguous range degradation is achieved by introducing an extra orthogonality to the sounding signal, namely by extra coding. The sounding time-shifted LFM signals presented in this Section have three orthogonalities: polarimetric one, quasi-orthogonality due to the time shift and the third orthogonality is achieved by the coding applied on the signals over M consecutive time intervals ($M \ge 2$). Such multi-cyclic sounding signals can provide high isolation level in polarimetric radar channels like signals presented in the previous Section, but without unambiguous range degradation.

Code sequences for extra coding can be any phase code modulated (PCM) signals. However, extra coding of sounding signals by complementary sequences allows the signals separation on receive without extra pulse compression for the chosen codes. Complementary pair of length *M* can be written as two vectors:

$$A = \left[a_1 \ldots a_M\right], \; B = \left[b_1 \ldots b_M\right]. \tag{4}$$

The complex envelope of the vector sounding signal becomes

$$\mathbf{u}(t)=\begin{bmatrix}u_H(t)\\u_V(t)\end{bmatrix}=\frac{1}{\sqrt{M}}\cdot\begin{bmatrix}\sum_{m=1}^{M}a_m\cdot u_1(t-(m-1)\cdot T)\\\sum_{m=1}^{M}b_m\cdot u_1(t-t_{sh}-(m-1)\cdot T)\end{bmatrix},\quad 0\le t<T\cdot \tag{5}$$

The factor $1/\sqrt{M}$ is included as energy normalization factor. Signal (5) can be classified as two coherent trains of diverse pulses [5], where diversity (as extra, from sweep to sweep, coding) is used for increase of orthogonality of sounding signals.

The CW vector signal consisting of two signals transmitted on orthogonal polarizations can be written as follows:

$$\mathbf{u}_{CW}(t)=\sum_{n=-\infty}^{\infty}\mathbf{u}\left(t-n\cdot M\cdot T\right), \tag{6}$$

where the signals repetition interval becomes $M{\cdot}T$, M times more compared with the signals presented in Sections 2 and 3.

It should be said that for the unambiguous range equal to $R_{un} = c{\cdot}T/2$, where c is velocity of light, is achieved by the length $M=2$. In this case the complementary sequences can be A = [1 1], B = [1 −1]. In this case the compensation of the unambiguity range degradation can be utilized by simple summation units applied in all four processing channels in the polarimetric FM-CW radar receiver [6].

5. LFM signals with opposite slopes and extra coding

The process of sounding changes the polarization state of the signals; however, it does not affect the waveform coding. The additional relationships obtained due to the additional coding of the transmitted signals allow us for compensation the non-orthogonality residuals existing in the received signals. So, this part of the library contains a pair of LFM signals with opposite slopes. The phase relations between each subsequent sweep are set up by the code sequences A, B of length M applied on the sounding signals. In this case the complex envelope of the vector sounding signal is

$$\mathbf{u}(t)=\begin{bmatrix}u_H(t)\\u_V(t)\end{bmatrix}=\frac{1}{\sqrt{M}}\cdot\begin{bmatrix}\sum_{m=1}^{M}a_m\cdot u_1(t-m\cdot T)\\\sum_{m=1}^{M}b_m\cdot u_2(t-m\cdot T)\end{bmatrix},\quad 0\le t<T\cdot \tag{7}$$

The signals transmitted on orthogonal polarizations are the repetitive up-going and down-going signals with extra coding from sweep to sweep.

Using Eq. 7 in Eq. 6 yields the CW vector sounding signal transmitted on orthogonal polarizations in case of sounding LFM signals with opposite slopes and extra coding.

6. Some degrees of freedom

Arbitrary waveform generators used in modern radars can generate any arbitrarily defined waveform as its output. So, the waveform library presented in this paper can be enhanced by the following degrees of freedom, whose any combination can be applied in radar with flexible architecture.

- *Bandwidth of sounding signals* (Fig. 1.a) can change within the allocated frequency band.
- *Slope of LFM signal* (Fig. 1.b). A pair of sounding signals in polarimetric FM-CW radar can have identically going slopes (e.g. like in Sections 3 and 4), or opposite (up and down) going slopes (e.g. like in Sections 2 and 5).
- *Duty cycle* (Fig. 1.c) or the signal repetition period can be a variable value for a radar. However, this parameter should be changed carefully, because it defines the unambiguous range, affects the range resolution and compression coefficient provided by de-ramping processing.
- *Sweep duration* (Fig. 1.d) can be not necessarily equal to the radar duty cycle (signal repetition period); it can take a part of it. The ratio between the sweep duration and repetition period can be a parameter, as well.

- *Time-shift between signals* (Fig. 1.e) presented in Section 3, can be also a reconfigurable parameter.

All the here-described degrees of freedom of the sounding signals are available in the operating radar system – PARSAX for its FM-CW mode. The arbitrary waveform generator used in the radar transmitter allows for generating all the presented in this paper signals. The waveforms created by an arbitrary waveform generator are keeping offline and require an operator to choose them. In turn, the digital configuration of the PARSAX radar receiver allows for its reprogramming (redesign) depending on the pulse compression technique (de-ramping processing or matched filtering).

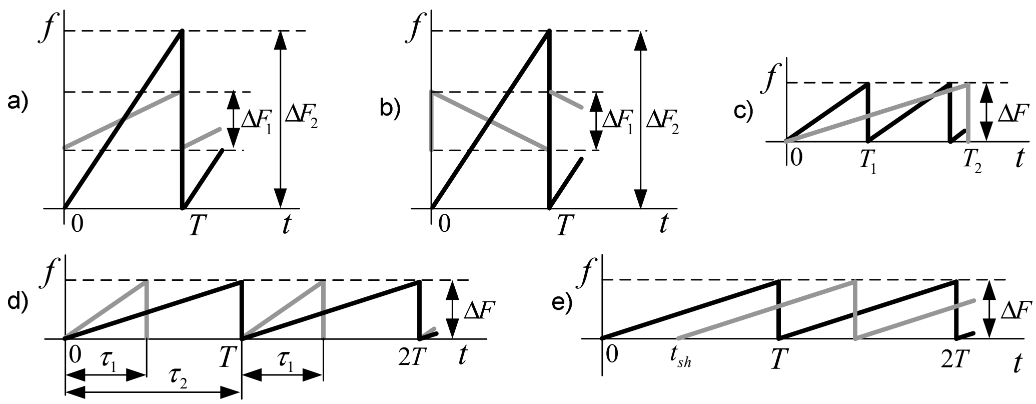

Figure 1: Some degrees of freedom for the LFM signals' generation.

7. Conclusion

We developed a library of sounding signals for a polarimetric software defined radar PARSAX. Each signal is a pair of mutually orthogonal wavelets which are to be transmitted via two polarimetrically orthogonal channels of the radar. Properties of the signals are discussed and compared. The presented signals are not limited by the use in polarimetric radar with continuous wave transmission. They also can be applied in multi-channel pulse radar, where sounding signals have inter-pulse linear frequency modulation.

Acknowledgments. This research has been done in the framework of Dutch Technology Foundation STW funded PARSAX project.

7. References

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