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Radar Polarimetry with Interleaved Dual-Orthogonal and Time-Multiplexed Signals: The PARSAX Radar Setup and Preliminary Results

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Abstract— **Radars capable of measuring targets' polarimetric characteristics provide valuable supplementary information for a more reliable detection, identification and physical parameters estimation. The novelty of this work lies in that it had not been previously possible to perform measurements for a comparison of polarimetric orthogonal simultaneous vs time-multiplexed sequential sounding signals in *real-time,* because of the time delay required to reconfigure a system to cater for the different waveform types. During this time delay, an observed non-stable target(s) would have had substantially moved, yielding both measurements not directly comparable. In this paper we present the polarimetric interleaved simultaneous-time-multiplexed waveform, justifications for the PARSAX radar setup upgrade, and the system implementation with a focus on the receiver FPGA. Preliminary results from the comparison are revealed. The data and results will be used for a future detailed comparative analysis of sounding waveforms and their impact on polarimetric target characteristics.**

Index Terms— **Radar polarimetry, FMCW, Orthogonal waveforms, Radar signal processing, FPGA.**

I. INTRODUCTION

It is a widely accepted fact that radars capable of measuring targets' polarimetric characteristics - within the variety of radar sensing applications - provide valuable supplementary information for more reliable detection, identification and physical parameters estimation. The most complete measurable instant polarimetric characteristics of any target is the Polarization Scattering Matrix (PSM), which has to be measured with a known polarization basis (e.g. for most radars it is the orthogonal linearly polarized basis {H,V}, where H and V stand for horizontal and vertical respectively). The variability of targets' characteristics in time can be studied in the time domain using covariance matrix analysis, or in the frequency domain using Doppler spectrum processing [1]. The measurement methodology of such an instant PSM however plays a prime role in such an analysis, and defines its applicability and limitations.

From the basic principles of radar polarimetry, an instant PSM for a specific polarization basis can be measured using a sounding signal with non-correlated polarization components in that specific polarization basis. The correlation has to be estimated during the observation time interval for an instant PSM estimation. That observation time - for any polarimetric radar - is equal to the polarimetric Pulse/sweep/frame Repetition Interval (PRI).

Sounding signals with non-correlated polarization components in any selected polarization basis can be created in three ways: using the transmission of polarization-orthogonal components with time multiplexing of the same waveform, with frequency multiplexing of the same waveform or using simultaneous orthogonal waveforms within the same frequency band. The reception of signals scattered by targets in orthogonally polarized radar receiver channels - after optimal matched processing - will provide the estimation of all elements of an instant PSM within one polarimetric PRI. The duration of the polarimetric PRI depends on the type of transmitted polarimetric signal and the number of parallel polarization-orthogonal channels in the radar's transmitter and receiver. Each of the aforementioned polarimetric sounding signals have its own advantages and limitations.

Modern polarimetric radars widely use signals with time multiplexed polarization-orthogonal components. These require one transmitter channel with switchable orthogonal polarizations, a receiver with one switchable polarization channel or two parallel polarization-orthogonal receiver channels. The polarimetric PRI of such a radar can meanwhile be two, three or even four times longer than the duration of every individual polarized component. Applied processing algorithms furthermore assume that during that longer time interval, the position and other characteristics of observed targets do not change. In some applications such an assumption is incorrect. Even with Doppler processing, such signals result in the decrease of the estimated velocity ambiguity in comparison with non-polarimetric measurement with the same sounding signal.

Polarimetric radars with frequency multiplexing of the same waveform require two parallel transmitter channels. The receiver channels' bandwidth have to be wide enough to cover the integral bandwidth of both frequency shifted polarization-orthogonal components. The demand for complete coherence of the transmitted components place more stringent requirements on waveform generators and local oscillators for phase coherence. Even if all technical

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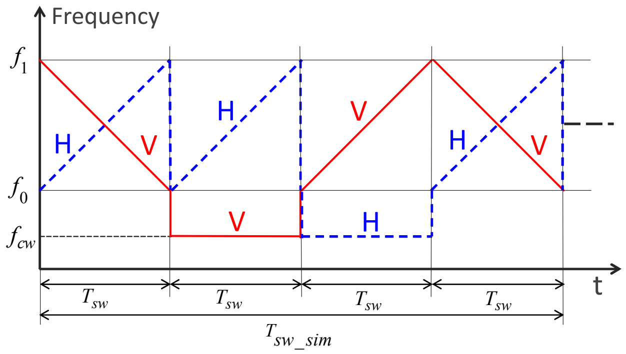

Fig. 1. Interleaved simultaneous-time-multiplexed sequential waveform.

requirements are satisfied, the usage of different frequencies for the simultaneous estimation of targets' PSM is not straightforward. Issues like frequency dependence of target's RCS, phase center and bright spots positions, Doppler shift, etc. have to be taken into account and studied in detail.

On the other hand, the usage of sounding signals with simultaneous orthogonal waveforms - within the same frequency band - in polarimetric radars also require the system to have two independent transmit and two receive channels. There is therefore the possibility to measure all elements of the PSM simultaneously in one pulse/sweep, as in the standard PARSAX operational mode [1]. All other limiting assumptions are however not valid in such a case. The measurements in all polarimetric channels are done simultaneously in time and at the same frequency band. Unfortunately, currently used Frequency Modulated Continuous Wave (FMCW) signals with dual orthogonality provide limited cross-channel isolation, which requires the use of special algorithms for cross-channel interference mitigation. These mitigation algorithms result in the presence of processing artifacts which are difficult to suppress [2][3][4].

All the pro and contra arguments presented above for the usage of different types of polarimetric signals and processing architectures may be reasonably sound, but have not been extensively experimentally tested. The main reason for that has been the absence of an operational radar which can simultaneously operate in in real-time in all the listed modes (not even after SW reconfiguration).

A proposed comparative study of the applicability, efficiency and limitations of all possible polarimetric configurations can however be done - after a setup upgrade - using the PARSAX radar system, which is an FMCW software-defined S-band polarimetric Doppler radar [1]. In this paper we present one of the waveforms which were necessary for this study, we discuss the radar configuration and upgrade and the FPGA implementation. These have allowed the novel possibility of performing polarimetric simultaneous vs time-multiplexed sequential measurements of non-stable radar targets in real-time, by virtue of a flexible, reconfigurable radar system. We furthermore present preliminary measurement results.

The structure of this paper is that section 2 presents the waveform used for the measurements. Section 3 presents justification for an upgrade of the receivers' FPGA design and radar setup. Section 4 covers the particulars of the receiver channels' FPGA design. The measurement results are presented in Section 5. Conclusions and remarks are given in Section 6.

II. The Dual-Orthogonal Time-Multiplexed Waveform

As a first step in the comparative study of different polarimetric waveform types, a waveform combining two polarimetric FMCW waveforms has been selected. Namely the time multiplexed and simultaneous orthogonal (within the same frequency band). A Linear Frequency Modulated (LFM) signal with a positive frequency excursion has been selected for the time multiplexing component of the waveform - Such signals are widely used in current FMCW polarimetric radars (e.g. TARA[6], IDRA[7])-; Whereas a pair of simultaneously transmitted LFM signals with the same central frequency but with positive and negative frequency excursions has been selected as the polarimetric dual orthogonal component [2][3]. The proposed interleaved simultaneous-time-multiplexed sequential polarimetric waveform as depicted in Fig. 1 is generated by a multichannel Arbitrary Waveform Generator (AWG). All operational LFM waveforms have the same frequency bandwidth of 50 MHz, sweeping continuously within an interval between f_0 = 100MHz and f_1 = 150MHz. The waveform forms an infinitely repeating sequence of three sweep intervals. During the first sweep, a polarimetric waveform with dual orthogonality is transmitted on the Horizontal (H) and Vertical (V) polarizations simultaneously. The two following sweep intervals are used for the transmission of time-multiplexed sequential waveforms. The same positive frequency excursion LFM is transmitted on the horizontal channel during the first sweep of this pair, and then on the vertical cannel during the last. It is impossible to blank the PARSAX radar transmitter's power amplifiers on a sweep-to-sweep time rate bases, consequently, non-operational channels during the sequential pair of sweeps are programmed to generate an out-of-band Continuous Wave (CW) signal at a frequency of 25MHz. The time T_{sw} of individual sweeps in the sequence is equal to 1ms, as a result, the polarimetric PRI for the whole sequence of sweeps – for a simultaneous sweep as well as for a sequential one on both polarizations – T_{sw_sim} is equal to 3ms.

III. Radar Setup Upgrade Justification

Traditionally, the PARSAX radar digital FPGA-based receivers' standard configuration and AWG setup had only allowed for the possibility of performing polarimetric measurements with just a single selected polarimetric

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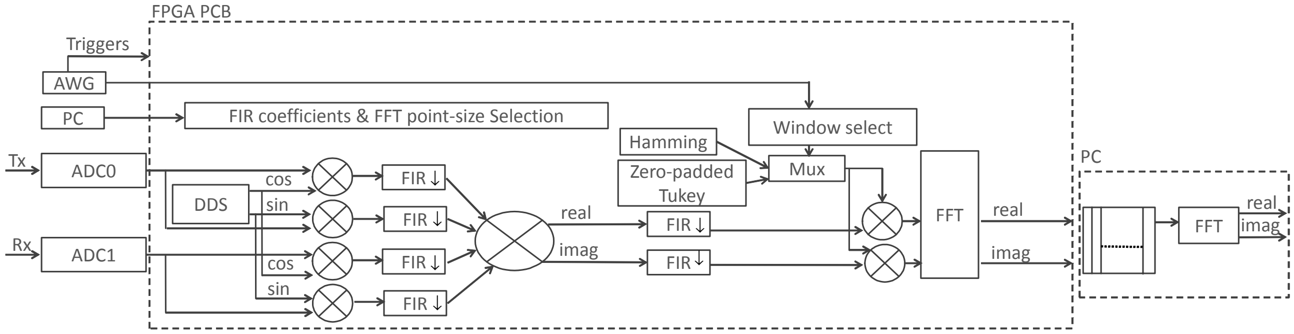

Fig. 2. Simplified diagram of the complex-deramping implementation and radar setup for the performed mesurtments.

waveform. The recording of range-compressed data in real-time was done, then there was a need to reprogram the FPGAs and the AWG before switching to another measurement setup. As a result, it had not been possible to make a comparative study of different polarimetric approaches using data collected in real-time. This real-time aspect is of utmost importance for the most interesting case of dynamic targets.

Deramping is a common method of range processing in FMCW radar. In deramping, received signals are mixed with a replica of the transmitted one, then the results are low-pass filtered for the extraction of beat frequencies which contain information about targets' range and scattering amplitude [5]. Further conversion of that signal into the frequency domain using an FFT provides the range-compressed signals of interest. Simultaneous or time-multiplexed polarimetric waveforms are comprised of LFM slopes with different excursions, but are initially processed at reception using the similar deramping algorithm as described above. The difference is only in the type of window used for FFT side-lobes mitigation. For time-multiplexed waveforms, a classic Hamming window is used, whereas a special bimodal window with zero-padding (zero-padded Tuckey window) is used to minimize cross-channel interferences [3] for simultaneous ones. For the new interleaved simultaneous-time-multiplexed waveform used in this paper, a switching of the window type has to be done on demand, or on a bi sweep-to-sweep basis.

The deramping of real-valued signals - as opposed to complex-valued - in the FPGA has further put constraints on the usage of frequency multiplexing waveforms in terms of the minimum allowable separation between LFMs without the undesired folding of positive and negative frequencies after deramping.

All the above have led to one of the study's goals being to create a special radar operational mode to cater for multiple polarimetric waveform types in a sweep-to-sweep rate, and to upgrade the digital FPGA-based receiver implementation for more flexibility and complex-valued signal representation.

IV. NEW IMPLEMENTATION OF THE DIGITAL RECEIVER

The operational version of the FPGA-based deramping receiver designs with real-number signal representation was described in [8][9]. The architecture used to process the new waveform is subsequently discussed.

A. Architecture

In the complex-deramping – single-sideband – FPGA receiver design depicted in Fig. 2, the real reference transmitted signal (Tx) and received signal (Rx) - at an Intermediate Frequency (IF) of 125MHz - are sampled with two 400MSPS ADCs. A Direct Digital Synthesizer (DDS) block from Xilinx is used to demodulate the Tx and Rx signals into baseband in the form of in-phase/quadrature (I/Q) components. The maximum bandwidth of interest for the radar is 100MHz (limited by the RF front-end), but multiplications in the digital domain produce frequency summation harmonics, which have to be filtered out by the FIR blocks after the DDS. A decimation by two is then implemented without being affected by any aliasing by the harmonics. The arrows pointing down in FIR blocks indicate a downsampling operation. A complex multiplier is then implemented for the generation of targets' beat-frequencies in a typical deramping process. The radar's maximum range of interest determines the maximum beat-frequency, which in this case is 5MHz, corresponding to a maximum range of 15Km. The I/Q components of the beat-frequencies are filtered once again for that maximum beat frequency, and a further order of magnitude downsampling becomes possible.

The design's flexibility and radar reconfigurability permits a control PC to select FIR coefficients and FFT point-size [10]. The AWG can moreover select the appropriate windowing function for the data before the range compression FFT. When the radar is transmitting simultaneously on both H and V channels, a zero-padded Tuckey window [3] is selected to reduce cross-channel interference, whereas a Hamming window is selected otherwise. Range profiles in the frequency domain are marshalled to a PC for Doppler and further processing.

This complex-deramping design has been used to facilitated the usage of even further new polarimetric waveforms, in addition to its 3db Signal to Noise Ratio

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(SNR) gain, due to the unfolding of positive and negative beat frequencies after I/Q demodulation.

B. CPI Extraction

Each of the radar's polarimetric receiver channels (HH, HV, VH, VV) are equipped with an FPGA board running the aforementioned design. A CPI of 512 simultaneous and 512 sequential sweeps (per respective channel) are extracted at reception from the interleaved waveform of Fig. 1. The HH-simultaneous CPI for e.g. will extract sweeps 1, 4, 7 etc., whereas sweeps 2, 5, 8, etc. will be extracted for the HH-sequential CPI.

V. POLARIMETRIC MEASUREMENTS RESULTS

We have performed measurements for different types of targets/scenes with new polarimetric sounding signals and the upgraded FPGA digital receiver design. In this paper we present results for only the interleaved polarimetric simultaneous-time-multiplexed waveform in Fig. 1. An example of polarimetric range-Doppler maps of targets on a highway at a range of around 2.2 km are shown in Fig. 3 and Fig. 4. The data and results will be used for a future detailed comparative analysis of sounding waveforms and their impact on polarimetric target characteristics, and the differences for each measurement scenario.

VI. CONCLUSIONS

The novelty of this work lies in that it had not been previously possible to performs measurements for a comparison of polarimetric orthogonal simultaneous vs time-multiplexed sounding signals in *real-time*. Traditionally, a CPI had to be measured with a simultaneous waveforms, then a system reconfiguration was required for a different processing algorithm, or for the reprogramming of the AWG, before a sequential time-multiplexed waveform can be used for another CPI, as in the results presented in [1] for a stable target. During the system reconfiguration time delay, an observed non-stable target(s) would have had substantially moved, yielding both measurements not directly comparable. In this paper we have presented the polarimetric interleaved simultaneous-time-multiplexed sequential waveform, justifications for a radar setup upgrade, and the radar system implementation with a focus on the receiver FPGA. Preliminary results from the comparison were revealed, with final conclusions to be presented during the conference.

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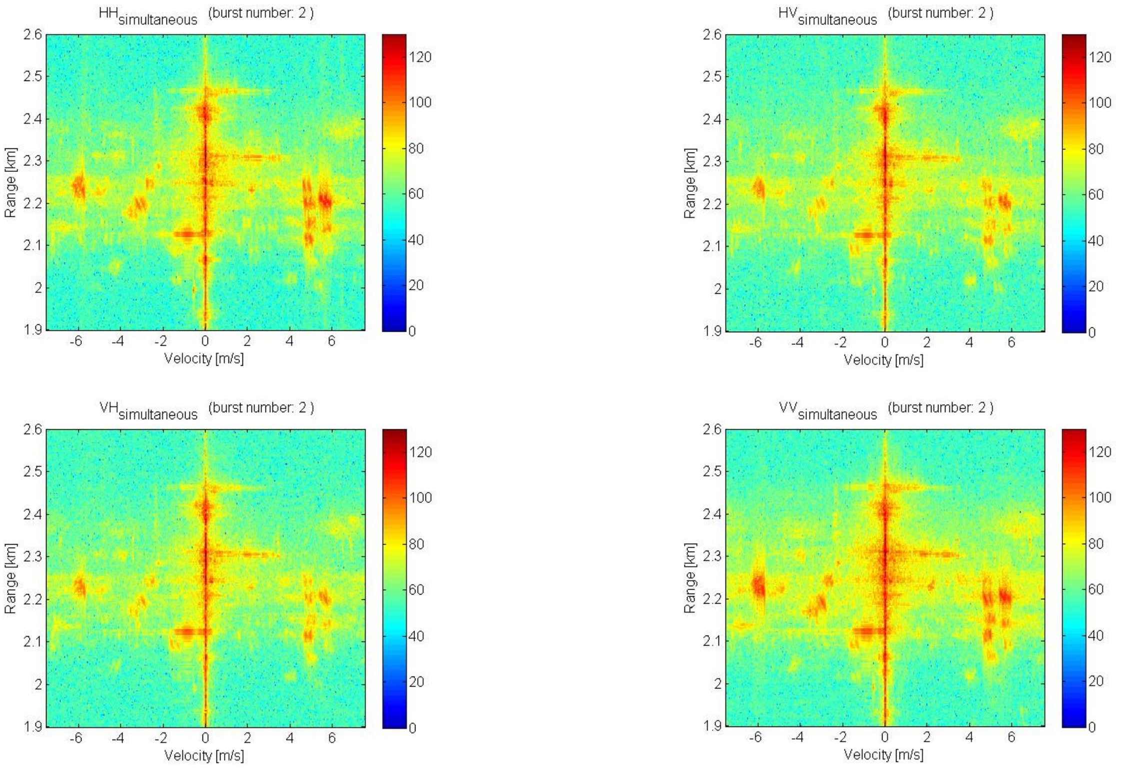

Fig. 3. Polarimetric range-Doppler map of a highway scene which was measured with the simultaneous sweeps of the interleaved simultaneous-time-multiplexed sounding waveform.

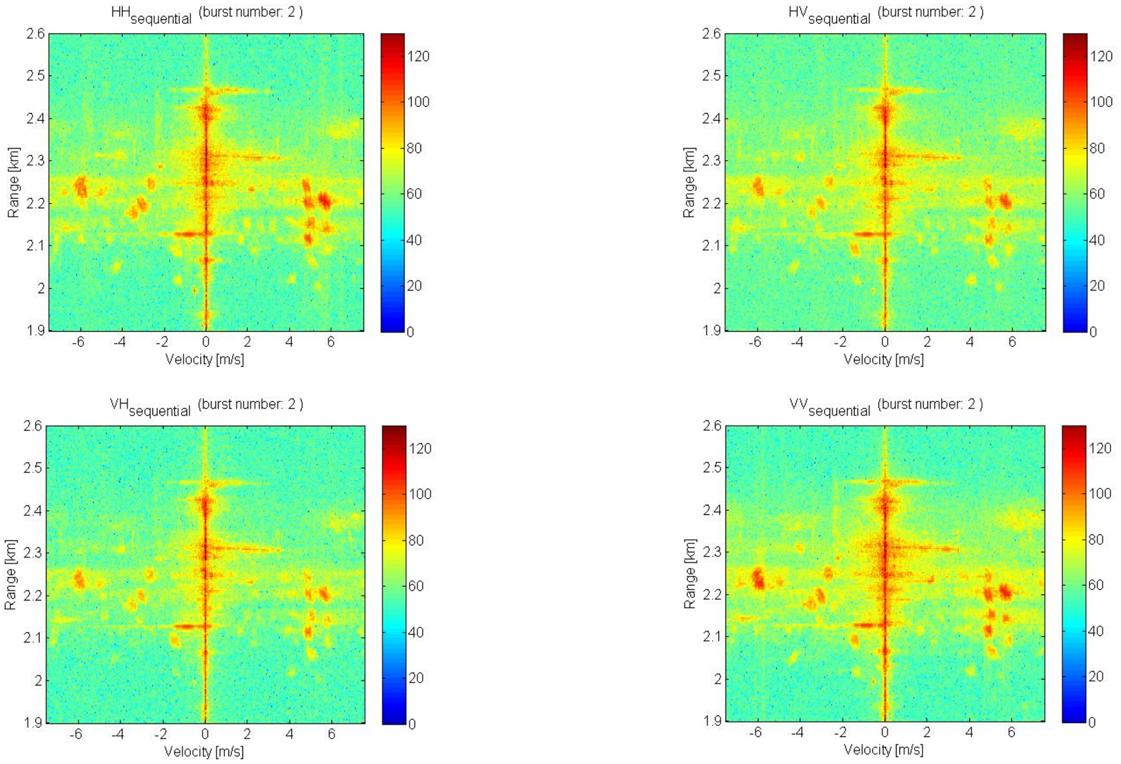

Fig. 4. Polarimetric range-Doppler map of a highway scene which was measured with the sequential sweeps of the interleaved simultaneous-time-multiplexed sounding waveform.

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