The PARSAX – New Full Polarimetric FMCW Radar with Dual-Orthogonal Signals

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ABSTRACT

The article describes the IRCTR PARSAX radar system – S-band fully polarimetric high resolution Doppler FMCW radar with dual-orthogonal sounding signals, which has the possibility to measure all elements of the radar targets polarization scattering matrix simultaneously, in one sweep.

1. INTRODUCTION

The long history of the radar polarimetry shows that the knowledge of the radar target polarization scattering matrix gives an additional information for the improvement of target detection, identification and parameters estimation and retrieval algorithms. The application of these algorithms to the real radar scenes and targets, which usually can be characterized as to be dynamic, temporally unstable and spatially-distributed themselves (atmospheric objects) or surrounded by such objects (targets on the land and sea surface), has serious limitations that follow from non-simultaneity of the polarization scattering matrix elements measurements. In most of the existent radars with polarimetric capabilities, the pulse-to-pulse based switching of the transmitted and/or received polarization is used to decouple the elements of the scattering matrix. This introduces temporal, frequency and phase unambiguities in the polarimetric results.

There is known solution of the polarimetric radar design, which still has not been widely used by radar developers – to use the signals with dual orthogonality [1], [2], [3]. The orthogonally-polarized components of such signals are waveforms that are orthogonal in terms of their inner product. Such type of sounding signals provides the unique possibility to split all elements of scattering matrix and to measure all of them simultaneously during one pulse or single sweep time.

The structure of the paper is the following. The Section 2 gives an overview of the polarimetric radar with dual-orthogonal sounding signals concept. In Section 3, the brief description of the PARSAX radar, which implements the presented concept and is currently under development in IRCTR, is given. The Section 4 shortly presents the radar performance analysis in terms of the level for co- and cross-channels interferences. And the Section 5 includes conclusions.

2. POLARIMETRIC AGILE RADAR CONCEPT

The vector nature of electromagnetic fields requires to analyze processes of transmitting, scattering and receiving of the radar signals in some predefined coordinate system. In the standard for radar applications cases of the plane waves, the Cartesian coordinate system, which defined by unit vectors triplet ($\vec{k}$, $\vec{e}_H$, $\vec{e}_V$) with unit vector $\vec{k}$ oriented in propagation direction, unit vectors $\vec{e}_H$ and $\vec{e}_V$ placed in horizontal and vertical planes, respectively, are mostly in use. As result, the electric field vector can be expressed as decomposition $\vec{E}(t) = \dot{E}_H(t)\cdot\vec{e}_H + \dot{E}_V(t)\cdot\vec{e}_V$ or, in more convenient for analysis matrix form

$$\vec{E}(t) = \begin{Vmatrix} \dot{E}_H(t) \\ \dot{E}_V(t) \end{Vmatrix} \tag{1}$$

where complexity of components means that they keep information not only about amplitude, but also about their phases.

The resulting transformation of the radar signal's vector structure in the radar channel, which includes polarization characteristics of the transmitter and receiver antennas, propagation media and radar target, can be written as linear operator:

$$\vec{E}_R(t-\tau) = \hat{S}(t,\tau)\cdot\vec{E}_T(t) \tag{2}$$

or, in matrix form,

$$\begin{Vmatrix} \dot{E}_{HR}(t-\tau) \\ \dot{E}_{VR}(t-\tau) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{HH}(t,\tau) & \dot{S}_{VH}(t,\tau) \\ \dot{S}_{HV}(t,\tau) & \dot{S}_{VV}(t,\tau) \end{Vmatrix} \cdot \begin{Vmatrix} \dot{E}_{HT}(t) \\ \dot{E}_{VT}(t) \end{Vmatrix}, \tag{3}$$

where $\dot{E}_{xT}(t)$ and $\dot{E}_{xR}(t)$ represent the electric field components of the transmitted and received waveforms, respectively.

The full polarization scattering matrix of the radar channel $\hat{S}$ can be decomposed as sequential multiplication of the scattering matrixes of all radar channels' components:

$$\hat{S}(t,\tau) = \hat{R}\cdot\hat{P}_-(t,\tau)\cdot\hat{S}_0(t,\tau)\cdot\hat{P}_+(t,\tau)\cdot\hat{T} \tag{4}$$

where $\hat{T}$ - polarization diagram of transmitter antenna; $\hat{R}$ - polarization diagram of receiver antenna; $\hat{S}_0(t,\tau)$ - true polarization scattering matrix of the radar target, which is a function of time t and range-dependent time delay τ ; $\hat{P}_+(t,\tau)$ and $\hat{P}_-(t,\tau)$ are the forward and backward propagation matrices, which describe the amplitudes, phases and polarization changes of the electromagnetic waves during the propagation. In case of the propagation media with polarization isotropy $\hat{P}_{+/-}(t,\tau) = \dot{a}_{+/-}(t,\tau)\cdot\hat{I}$, where $\hat{I}$

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is the unity matrix, the complex scalar functions $\dot{a}_{+/-}(t,\tau)$ describe the attenuation and phase changes of propagating signals.

As follows from the Eq. 3, in general case, the received radar signals are the combination of the polarization matrix and transmitted vector components

$$\begin{Vmatrix} \dot{E}_{HR}(t) \\ \dot{E}_{VR}(t) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{HH}(t)\cdot\dot{E}_{HT}(t)+\dot{S}_{VH}(t)\cdot\dot{E}_{VT}(t) \\ \dot{S}_{HV}(t)\cdot\dot{E}_{HT}(t)+\dot{S}_{VV}(t)\cdot\dot{E}_{VT}(t) \end{Vmatrix} \quad (5)$$

If the signals in the polarization-orthogonal transmitter channels are the same ($\dot{E}_{HT}(t)=\dot{E}_{VT}(t)=\dot{E}_{T}(t)$), then

$$\begin{Vmatrix} \dot{E}_{HR}(t) \\ \dot{E}_{VR}(t) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{HH}(t)+\dot{S}_{VH}(t) \\ \dot{S}_{HV}(t)+\dot{S}_{VV}(t) \end{Vmatrix}\cdot\dot{E}_{T}(t) \quad (6)$$

and there is no possibility to separate co- and cross-polar matrix elements.

In most of the existent radar polarimeters this problem is solved by the separation of transmit signals with orthogonal polarization in time. During the first pulse or sweep time only H-polarized component is transmitted and, as result, the received signal is equal to:

$$\begin{Vmatrix} \dot{E}_{HR}(t_1-\tau) \\ \dot{E}_{VR}(t_1-\tau) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{HH}(t_1,\tau) \\ \dot{S}_{HV}(t_1,\tau) \end{Vmatrix}\cdot\dot{E}_{T}(t_1) \quad (7)$$

The second transmitted pulse has only V-polarization:

$$\begin{Vmatrix} \dot{E}_{HR}(t_2-\tau) \\ \dot{E}_{VR}(t_2-\tau) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{VH}(t_2,\tau) \\ \dot{S}_{VV}(t_2,\tau) \end{Vmatrix}\cdot\dot{E}_{T}(t_2) \quad (8)$$

For the radar polarimeter with such sequential algorithm of the measurement, a special care has to be taken about the phase difference between columns of scattering matrix, which are measured independently and in different moments of time. This non-simultaneity in measurements provides severe errors in case of dynamic targets and requires some type of correction/compensation.

Another approach for the radar target scattering matrix measurements consists in the use of the frequency difference between orthogonally-polarized sounding signals

$$\begin{Vmatrix} \dot{E}_{HR}(t) \\ \dot{E}_{VR}(t) \end{Vmatrix} = \begin{Vmatrix} \dot{S}_{HH}(t) & \dot{S}_{VH}(t) \\ \dot{S}_{HV}(t) & \dot{S}_{VV}(t) \end{Vmatrix}\cdot\begin{Vmatrix} \dot{E}_{HT}(t,\omega_1) \\ \dot{E}_{VT}(t,\omega_2) \end{Vmatrix} = \\ = \begin{Vmatrix} \dot{S}_{HH}(t,\omega_1)\cdot\dot{E}_{HT}(t,\omega_1)+\dot{S}_{VH}(t,\omega_2)\cdot\dot{E}_{VT}(t,\omega_2) \\ \dot{S}_{HV}(t,\omega_1)\cdot\dot{E}_{HT}(t,\omega_1)+\dot{S}_{VV}(t,\omega_2)\cdot\dot{E}_{VT}(t,\omega_2) \end{Vmatrix} \quad (9)$$

The frequency filtration in the receiver channels in this case gives the possibility to separate elements of polarization matrix and to extract simultaneous polarimetric information. But there is still a difference between columns of scattering matrix, which are estimated at different frequencies. This effect can be critical for some applications and types of targets, especially the estimation and interpretation of the phase difference between columns of scattering matrix since those phases are defined at different frequency bands.

To generalise the described approaches to measure the full polarization scattering matrix of radar target and to analyze another possibility to solve this task, a concept of polarimetric radar sounding signal with dual orthogonality - in polarimetric and in time-frequency spaces - has been proposed in [1], [2], and [3]. It requires that the complex envelop of the polarization components $\dot{E}_{HT}(t)$ and $\dot{E}_{VT}(t)$ of the transmitted signal must satisfy the following condition

$$U=\int \dot{E}_{HT}(t)\cdot\dot{E}^{*}_{VT}(t)\cdot dt \equiv 0 \quad (10)$$

i. e. the inner product of the orthogonally polarized components of the radar sounding signals has to equal zero. The spatially-distributed nature of the moving radar targets requires even more strict condition for successful scattering matrix elements extraction:

$$U(\tau,\omega_d)=\int \dot{E}_{iT}(t)\cdot\dot{E}^{*}_{jR}(t-\tau,\omega_d)\cdot dt \cong 0\,, \quad (11)$$

where $i,j=H,V;\quad i\neq j$, τ is the signal time delay, which is proportional to the target's range, ω_d - Doppler frequency shift, and the asterisk shows a complex conjugation.

The proposed concept of the dual-orthogonal polarimetric signals gives the possibility to extend analysis from the cases of orthogonal in time signals (7) - (8) and orthogonal in frequency signals (9), to more general case of signals with waveform orthogonality. The most widely known examples of such signals are

- The pair of chirp signals (linearly frequency modulated, LFM) with positive and negative frequency slope.
- The pair of signals with phase modulation by orthogonal codes (PCM)

The application of such sophisticated signals for the radar targets polarization scattering matrix measurements will remove most difficulties from the results interpretation, providing all elements of polarization matrix that are simultaneously measured at the same frequency band. The price for such enhancement of the measurements quality has to be paid by the challenging complication of the radar technology. The recent studies, which have been done by IRCTR in the framework of the PARSAX project, show the possibility for described concept implementation using state-of-art analog and digital components and techniques.

3. THE PARSAX RADAR DESIGN

The PARSAX radar currently being developed by IRCTR is a full-polarimetric S-band radar, which uses dual-orthogonal digitally generated sounding signals, high-dynamic range reception of scattered signals and their advanced digital processing on intermediate frequency for simultaneous measurements of all elements of the polarization scattering matrix during one sounding sweep. The early analog-to-digital conversion provides wider dynamic range, linearity, and possibility to implement complicated algorithms for the signal and data processing, which are more sensitive and at the same time more stable against the influence of noise, ground clutter and external interferences.

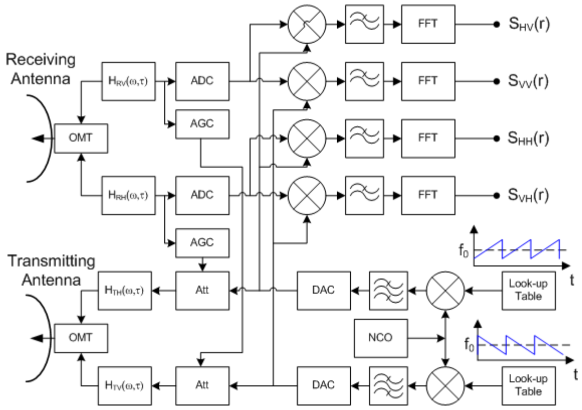

Figure 1. *Block-diagram of the PARSAX full polarimetric CW radar with dual-orthogonal sounding signals*

The Fig. 1 and Table I present a simplified block-diagram and the main characteristics of the radar.

The design of the radar's receiver and transmitter has been done using *Agilent* Advanced Design System (ADS) simulation software. The simulation and analysis of the full radar model gives the possibility to optimize the transmitter and the receiver chains from different aspects, to formulate requirements for every block and to make a clever choice of such blocks from the product variety on the component's market. The radar system RF components have been tested and the measured parameters have been used in a second stage of the simulation to control and validate selected technical solutions.

The presence of two independent orthogonal waveforms in every channel of the radar's receiver, which is distinctive for such type of radar polarimeters, has required the proper choice of parameters, which have to be used for the system performance characterization and optimization during design process. For example, the spur-free dynamic range (SFDR) parameter has been selected to characterize the system's dynamic range, since it is sensitive to the interfering tones that produce in-band spurious products.

More details about the radar design approach and results can be found at [4], [5].

The CW PARSAX radar operates in situation when the radar receiver is working under the influence of the continuous signal with the total power equal to the sum of all reflections in the illuminated volume. The strong reflections can be produced by the closest objects through the antennas main beam or sidelobes and, as result, might saturate the radar's receiver. The simulation of the proposed architecture for the PARSAX radar design using the ADS software shows that the best performances of the receiver, related to the maximum dynamic range and signal-to-noise ratio, can be achieved at some level of the input signal's power. The further increasing of the input power produces the degradation of the radar system performances. The typical behavior of the PARSAX receiver's SFDR as a function of the input power is presented in Figure 2. These arguments show the necessity to include in the PARSAX radar design the automatic gain

TABLE I

Main Characteristics of the PARSAX Radar

S band	Central frequency: 3.315 GHz Modulation bandwidth: 2 - 50 MHz Resolution: 75 - 3 m Sweep time: 1 ms
Antennas	Two parabolic reflectors Isolation receiver-transmitter: 100 dB
Receiver Antenna	Diameter: 2.12 m Beam width: 4.6° Gain: 32.75 dB
Transmitter Antenna	Diameter: 4.28 m Beam width: 1.8° Gain: 40.0 dB
Transmitter	Solid state power amplifiers 100 Watt max per channel - 80 dB attenuators (8 bits control bus)
Receiver	Dynamic range: better 70 dB (SFDR) 1 stage down conversion ADC at Intermediate Frequency (125 MHz, sampling 400 MHz, 14 bits) FPGA-based 4 channels digital processor
Waveforms	Digital vector waveform generator (sampling up to 1.2 GHz, 14 bits) Linear frequency modulation PCM with orthogonal codes

control circuit, which prevents the increasing of the input power above some specified level. The proposed solution suggest that such circuit does not control the gain of the receivers RF/IF amplifiers, but changes sweep-by-sweep output power of the radar's transmitter in a way that the sweep-period averaged input power of the receivers will be in the optimal range.

High performances of the radar's analog RF part provide good matching with the parameters of the digital waveforms generator and with the digital receiver. These blocks implemented on the base of state-of-art PC boards, which include the latest versions of *Analog Device* 14-bit ADC's with sampling frequency up to 400 MHz and *Xilinx* FPGA's for the digital signal processing implementation. This hardware provides necessary characteristics and flexibility for the implementation of different types of orthogonal waveforms and their processing algorithms.

4. SYSTEM PERFORMANCE ANALYSIS

The performance analysis of the radar system with dual-orthogonal signals in case of point targets can be done using two parameters – peak sidelobe level (PSL) and isolation (I) [2]. They are defined as

$$\mathrm{PSL}_i \triangleq \min_{\tau \notin \Omega_i} \left[20 \cdot \log_{10} \frac{|R_{ii}(0)|}{|R_{ii}(\tau)|} \right] \tag{12}$$

$$I_i \triangleq \min_{\forall \tau} \left[20 \cdot \log_{10} \frac{|R_{ii}(0)|}{|R_{ij}(\tau)|} \right], \quad i, j = 1, 2 \tag{13}$$

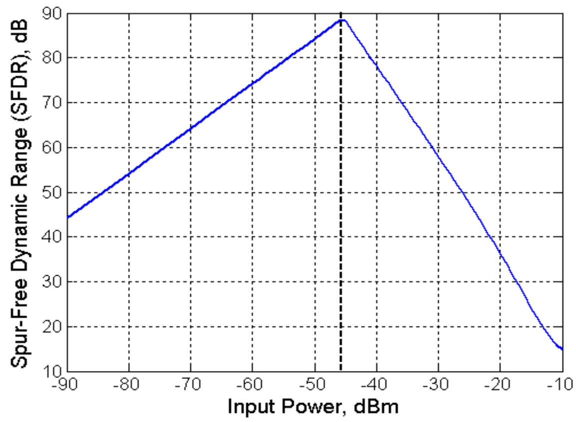

Figure 2. *The PARSAX radar receivers Spur-Free Dynamic Range as function of the input signals power (ADS simulation).*

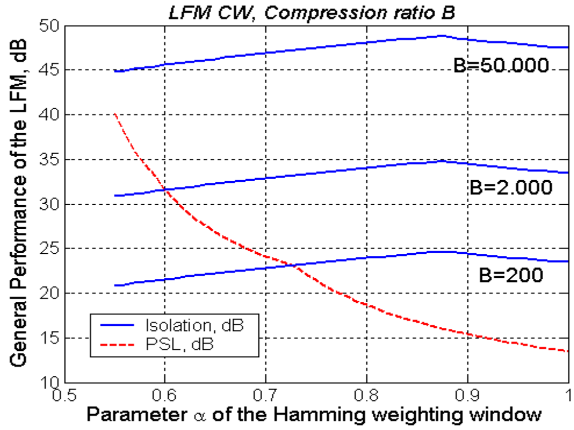

Figure 3. *Performance parameters of the FMCW polarimetric radar with dual-orthogonal LFM signals*

where $R_{ii}(\tau)$ and $R_{ij}(\tau)$ are the autocorrelation and cross-correlation functions of the transmitted signals complex envelopes, the index i denotes the waveform that is considered between those simultaneously transmitted, Ω_i is the interval of τ values corresponding to the mainlobe of $R_{ii}(\tau)$. The PSL is a measure of protection from the maximum residual «co-channel» interference due to interfering target and the isolation I is a measure of protection from the maximum residual «cross-channel» return due to the same target or to an interfering target.

The results of these parameters calculations as functions of the parameter α for the Hamming weighting function

$$w(t) = \alpha + (1-\alpha)\cos\left(\frac{2\pi t}{T}\right), \quad |t| \le T/2 \qquad (14)$$

are shown in Figure 3 for the different values of the sounding signals compression ratio, which is defined as a product $B = T \cdot \Delta f$ of the signal duration T and the bandwidth Δf.

From this representation it is clear that for the PARSAX FMCW system with high values of compression ratio (between 2000 and 50000) the cross-polarization-channels interferences become less important in comparison with self-channel interferences due to the sidelobes of compressed signal. A proper selection of the windowing function parameter for every selected value of the compression ratio provides the performances of the polarimetric radar with dual-orthogonal sounding signals at the level, which is comparable with that for standard one-channel FMCW radars. At the same time, the suppression of the sidelobes and cross-channels interferences is better than 30 dB level, which is the typical value for the polarization channels isolation in antennas.

5. CONCLUSIONS

The PARSAX radar is the full polarimetric CW radar with dual-orthogonal sounding signals, designed by IRCTR. The most important property of the radar is that it simultaneously transmits two orthogonally polarized waveforms with complex envelops, which are orthogonal in terms of their inner product. This property gives the possibility to measure all complex elements of the radar targets polarization scattering matrix simultaneously at the same frequency band within one sweep time. Another important property of presented design is the digital generation of the vector waveforms for the sounding signals and the digital IF receiver. Such approach provides real flexibility in terms of using different types of orthogonal waveforms and their processing algorithms. The operational use of the radar is expected in the course of the year 2009.

Acknowledgment. At the International Research Centre for Telecommunications and Radar (IRCTR), Delft University of Technology a major research project is underway for feasibility study, design and development of full polarimetric FMCW radar with dual-orthogonal signals for simultaneous measurement of all elements of radar target's polarization scattering matrix. This project is performed under a contract with Dutch Technology Foundation STW.

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