An Orthogonal Waveform for MIMO-SAR Applications

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Abstract

Synthetic aperture radar (SAR) with multiple transmit and receive channels (MIMO-SAR) has a higher flexibility and an improved efficiency compared to a conventional SAR system with a single channel. The multiple receive channels can be used, among other things, to increase the swath width at constant azimuth resolution or to suppress spatial interferences. However, multiple transmit channels, which transmit simultaneously in the same frequency band provide currently a challenge. The generation of a waveform which is orthogonal for distributed scatterers, proves to be excluded with conventional methods. Therefore, in this paper a modified chirp waveform is introduced which extends in combination with digital beam-forming (DBF) on receive the orthogonality condition to another degree of freedom, thus allowing perfect orthogonality. Furthermore, the hardware design of the MIMO-Radar Demonstrator, a multi-channel measurement system for radar and SAR applications is shown. This system developed at the German Aerospace Centre allows the metrological verification of the waveforms presented in this paper, and other innovative concepts for future spaceborne Earth observation missions.

1 Introduction

In the future, synthetic aperture radar (SAR) must meet higher requirements in terms of resolution, swath width and flexibility. This is due to the enormous success of the current satellite SAR missions (TanDEM-X, Radarsat-2, etc.) and the many users who demand the on-going development of the SAR technology [1], [2]. A consideration of various on-going studies shows that SAR sensors with multiple transmit and receive channels and digital beam-forming (DBF) capabilities have promising properties. For example, with them it is possible to reach a large swath width with high azimuth resolution or to observe several areas with different resolutions (Hybrid SAR modes). Recently, a prototype of these future radar systems has been developed for the verification of such innovative modes and is available at the German Aerospace Centre (DLR).

At the beginning of the paper the necessary condition for a reflectivity map free of ambiguities is discussed. Afterwards the new transmit waveform with perfect orthogonal properties for point and surface targets is introduced and it's crucial limitation is demonstrated. The next section explains how this limitation can be circumvented by an innovative DBF process. Then, in section 3 the MIMO-Radar Demonstrator is described, which is used for the metrological verification of the waveforms. The obtained measurement results are depicted in section 4. The paper concludes with a summary of the discussed results.

2 Orthogonal Signals for Imaging Radar and MIMO-SAR

2.1 Orthogonal Condition

First studies go back to Woodward in 1967. In his work, he was looking for a perfect waveform applicable for Radar and derived the Ambiguity Function. Later, in 1970, Harger expanded this function to the SAR case and in 2007 San Antonio et al. derived a general solution for MIMO-SAR [3], [4], [5]. Since for our case we have to use San Antonio's function, which is dependent of 16 unambiguous parameters, we use a more simplified model. The MIMO-SAR system fully exploits its degrees of freedom by simultaneously activating multiple transmit antennas in the same frequency band. To obtain orthogonality for these signals, several authors have suggested to simultaneously transmit mutually orthogonal waveforms. However it was clearly shown in [6] that this only works for small swath widths with a decreased signal to noise ratio. The reason for this is that the orthogonality condition between the transmit signals s_a and s_b is typically formulated as:

$$\int s_a(t) \cdot s_b^*(t) \cdot dt = 0 \qquad \text{for} \qquad a \neq b, \qquad (1)$$

which is valid for a dedicated point target. This condition is sufficient for most of the radar applications where a few point-like targets are detected, which are within different resolution cells. But it may pose a challenge in a distributed scatterer scenario when there is a time shift between s_a and s_b. By observing large swaths with an imaging radar or a SAR sensor the long echoes are already filling a huge part of the time-frequency plane. The echoes of the different transmit signals will then overlap and it becomes impossible to separate them later in the receiver. Thus, the condition to achieve is to ensure orthogonality for arbitrary shifts τ:

$$\int s_a(t) \cdot s_b^*(t) \cdot dt = 0 \quad \forall \quad \tau \in \mathbb{R}, a \neq b. \qquad (2)$$

2.2 Short-Term Shift-Orthogonal Waveform

To avoid an overlap and thus ambiguities of the transmitted signals a new, partly orthogonal waveform has been proposed by Krieger in [7] and later introduced in [8]. For two transmitters, the basic idea behind this approach can be expressed by a restricted orthogonality:

$$\int s_a(t) \cdot s_b^*(t) \cdot dt = 0$$
$$\forall \quad \tau \in \left[-\frac{\tau_{\text{pulse}}}{2}, \frac{\tau_{\text{pulse}}}{2}\right] \text{ and } \quad a \neq b, \qquad (3)$$

where τ_{pulse} is the pulse duration. Now, the two different transmit signals s_a and s_b have only orthogonal properties for a subset of signal shifts. In the example chosen here, this time interval is limited by half of the pulse length. This allows a perfect separation of the echoes of neighboring objects for a signal delay $\tau < \tau_{\text{pulse}}$. A simple example of a suitable signal is the simultaneous transmission of shifted frequency ramps. **Figure 1** shows the signals in the time-frequency plane.

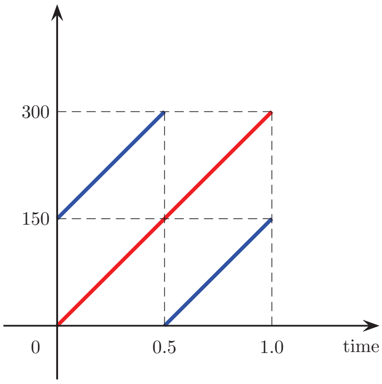

Figure 1: Short-Term Shift-Orthogonal Waveform in the time-frequency plane.

Transmit channel Tx1 is fed with a normal up-chirp, while transmit channel Tx2 is fed with a shifted up-chirp (also called Short-Term Shift-Orthogonal Waveform). It is clear that the signals do not overlap for signal propagation times shorter than $c_0 \cdot \tau_{\text{pulse}}/4$, where c_0 is the propagation speed of the signal. The factor of 4 is due to the two way propagation radar-target + target-radar and the 50 $\%$ shift of the pulse. However, if a larger surface is considered, the signal propagation time increases and the time-frequency plane is completely filled with the echoes, so that the two signals will overlap. In this case, they are no longer orthogonal, which represents the in Eq. 3 described limitation to this waveform. The scheme of chirp signals can be expanded easily to more than two transmit channels by splitting it into N_{Tx} parts, where N_{Tx} is the number of transmit channels. **Figure 2** shows the impulse response of a simulated point target at a distance of 150 m. With the chosen pulse width of $\tau_{\text{pulse}} = 1\ \mu$s, ambiguities appear at a distance of $\pm c_0 \cdot \tau_{\text{pulse}}/4$ (75 m and 225 m). These result from the convolution with the other channel. Since an up-chirp is used for s_a, all signal characteristics compared to a conventional pulsed radar chirp are identical. The phase shifts are assumed to be negligible for large time bandwidth products.
Because usually the swath width exceeds the pulse length, this type of waveforms will also cause ambiguities. Therefore, in the next section a solution to overcome this limitation with the aid of digital beam-forming on receive is described.

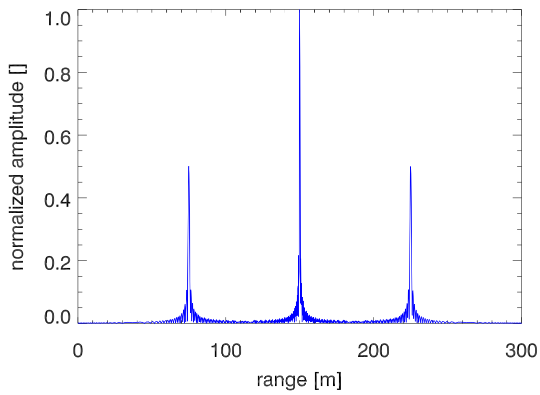

Figure 2: Impulse response of a point target at 150 m.

2.3 Suppression of Ambiguities with Digital Beam-Forming

To suppress the ambiguities which have been described in the last section, the use of digital beam-forming on receive is proposed. Due to the property of the side-looking radar, each point in the range direction is seen from a different angle of incidence. With the known relation of frequency, time, and angle of arrival, it is possible to distinguish between the individual transmit signals through beam-forming on receive. In the proposed method (also known as SCORE, Scan On Receive) [9] a broad swath on the ground is illuminated with the small apertures of the transmit antennas. On receive, all receive elements of the array antenna are activated and weighted with phase shifts so that there is a narrow directional beam, which follows the expected response on the ground. Due to the availability of the digital data for each dedicated channel, with adaptive shaping of the beam pattern (pattern synthesis) it is possible to optimize the antenna gain to a certain direction, and furthermore to perform a spatial filtering to suppress interferences and ambiguities. After a coherent combination of all the channels, range compression and other processing steps for typical SAR can be applied.

3 MIMO-Radar Demonstrator

The architecture of the modular, reconfigurable radar with multiple transmit and receive channels is shown in Figure 3 [8]. The purpose of this system is to test and verify new techniques and concepts for future satellite-based remote sensing missions. The configuration described in this paper, operates in X-band with two transmit and eight receive channels. At present, the radar can also be operated in the P-band (up to 500 MHz). The modular design in 19" form allows great flexibility of system changes and extensions.

As depicted in **Figure 3**, the desired transmit signals are generated in an arbitrary waveform generator having a bandwidth of max. 500 MHz. Then they are amplified and up-converted to the carrier frequency. Before transmission, the lower sidebands and the carrier signals are suppressed by band pass filters and the remaining signals are amplified with high-power amplifiers. Afterwards they are transmitted with either horn or patch antennas. In the receive chain, the echoes are received simultaneously by all Rx antennas, amplified with low-noise amplifiers, down-converted and finally sampled by AD converters. The independent data recording for each receive channel allows the subsequent formation of different arbitrary beam patterns of the antenna in the processing. The additional information can be used to suppress spatial ambiguities in the signal, to increase the gain of the receive antenna, or to suppress spatial interferences. Basic system properties have been already presented in [8]. In comparison to a radar system with a single-channel, stationary two-dimensional radar imaging, improved azimuth resolution and an improved signal to noise ratio have been verified successfully. These measurements were used as the first step towards high-resolution SAR imaging with large swath widths.

4 Measurement Results

For the demonstration and verification of the Short-Term Shift-Orthogonal Waveforms with the MIMO-Radar Demonstrator, an outdoor measurement of the target localization in the range direction was conducted. The radar was positioned on the roof of a building and the eight receive channels were connected to the feed elements of an elliptical DBF reflector antenna looking to a meadow. For transmission, two horn antennas were used. As objects 5 corner reflectors representing point-like targets were placed at distances of 24.9 m, 30.8 m, 40.8 m, 50.0 m and 63.2 m. The signals with a pulse duration of $\tau_{\text{pulse}} = 0.4\ \mu$s and a bandwidth of B = 300 MHz (corresponding to a range resolution of 0.5 m) were transmitted simultaneously at a center frequency of 9.58 GHz. While channel Tx1 was fed with an up-chirp channel Tx2 transmitted at the same time a Short-Term Shift-Orthogonal Waveform with a shift of τ_{pulse} / 2 (see Figure 1). In the obtained results without MIMO processing (**Figure 4**) a match with the theoretical prediction is clearly visible: The ambiguities are located at a distance of $\pm$ 30 m away from the real impulse responses and have an amplitude which is about 3 dB lower. In **Figure 5** the result with application of digital beam-forming can be seen. There are five sharp peaks and the ambiguities could be suppressed beyond the noise level. This shows that the Short-Term Shift-Orthogonal Waveforms can be used for MIMO-SAR observing large swaths with a high resolution.

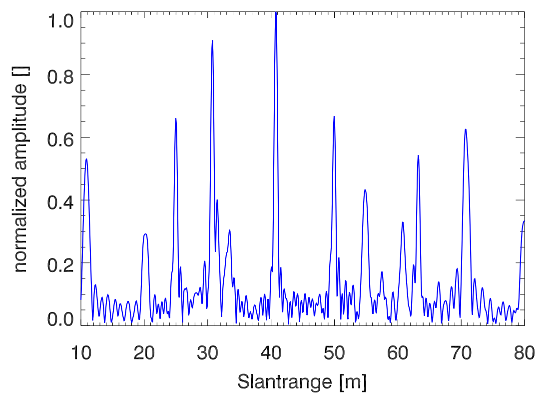

Figure 4: Impulse response without beam-forming.

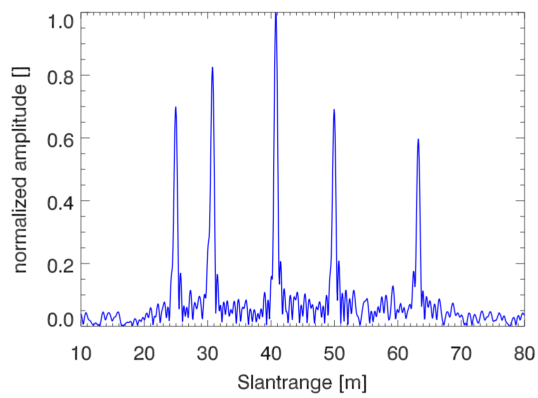

Figure 5: Impulse response with beam-forming.

5 Conclusions

In this paper, a new form of transmit signal for MIMO-SAR and imaging radar systems was introduced with a description of its fundamental limitation. It was described how this limitation can be overcome by digital beam-forming on receive. Finally, an overview of the structure of the MIMO-Radar Demonstrator was given and the theoretical aspects were verified by a measurement.

The results, which were presented in this paper, are a first

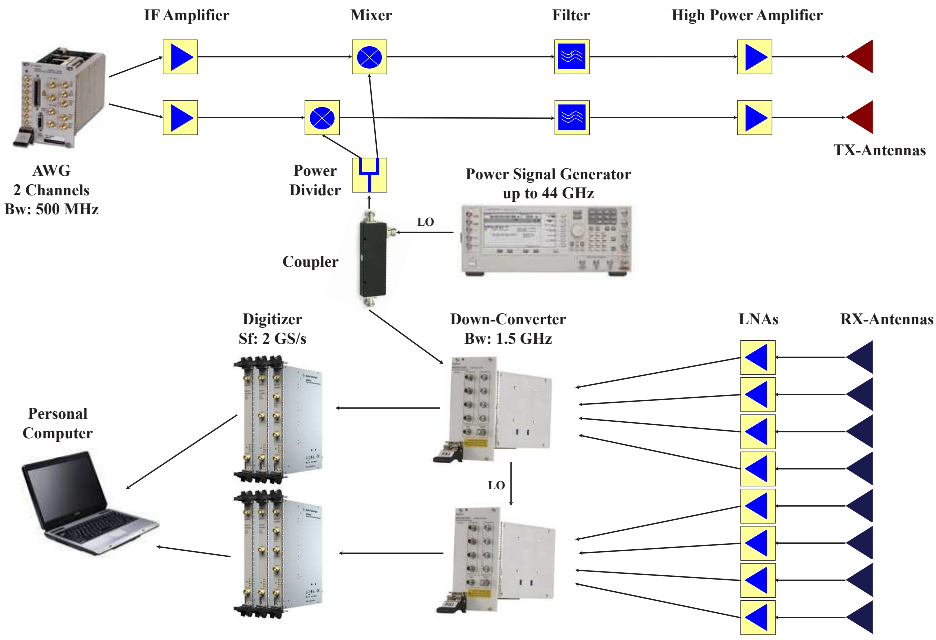

Figure 3: Simplified block diagram of the MIMO-Radar Demonstrator.

step in the development of future satellite-based Earth observation missions. Other innovative concepts, such as digital beam-forming with reflector antennas, hybrid SAR modes and nonlinear pulse repetition frequencies are already in progress. Very promising is the simultaneous transmission of signals in different orthogonal polarizations [10]. By separation of the transmitted signals in a dual polarized receiver, all four components of the scattering matrix (HH, VV, HV, VH) can be obtained within a single pulse and thus the swath with can be kept constant. Thus the innovative techniques and technologies of MIMO-Radar have the potential to increase the performance of current radar systems significantly.

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