An Orthogonal Waveform Scheme for Imaging MIMO-Radar Applications

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Abstract: *Synthetic Aperture Radar (SAR) based on Digital Beamforming (DBF) belongs to the family of Multi-Modal Radar Systems (MMRSs) which offer higher operational flexibility and improved performance compared to conventional radar systems using analog beam steering. DBF SAR, in particular, overcomes the fundamental resolution-coverage limitation of classical SAR systems and can deliver high resolution and simultaneously wide swath images. The purpose of this paper is to present recently obtained measurement results of a novel waveform called Short-Term Shift-Orthogonal Waveform obtained with the MMRS Demonstrator - a reconfigurable radar system based on a DBF and Multiple- Input Multiple-Output (MIMO) architecture, which is being developed at the Microwaves and Radar Institute of DLR. The results are the first step towards future spaceborne MMRSs, such as MIMO radars using orthogonal waveforms and reflector-based DBF SAR.*

1. Introduction

Next generation spaceborne Synthetic Aperture Radars (SAR) have to meet higher requirements for spatial and radiometric resolution, as well as coverage. This is due to the success of current SAR systems, and the manifold users demanding for a steady evolution of the SAR technology to satisfy increasing performance requirements. A review of several ongoing studies shows that a promising candidate for the next generation SAR is a multi-channel radar utilizing digital beamforming techniques which allow to overcome the fundamental high resolution / wide swath limitations of conventional SAR systems. The purpose of this paper is to present the MMRS system demonstrator and introduce an advanced MIMO concept to be experimentally verified with its help. The paper starts with a definition of orthogonal unambiguous signals for imaging radar applications. Afterwards a novel orthogonal waveform is introduced and its major limitation is discussed. After that we show how to overcome this limitation with Digital Beamforming on receive. Then an introduction of the MMRS demonstrator design is shown which is followed by a description of its operational hardware. Afterwards the measurement results of the introduced radar waveform for SAR imaging are discussed. The paper concludes with a summary.

2. The Orthogonality Condition For Radar Signals

The MIMO SAR system fully exploits its degrees of freedom by simultaneously activating multiple orthogonal transmit antennas in the same frequency band. To find a waveform which fulfills this condition, some authors have suggested the use of mutually orthogonal waveforms. However this technique is well suited for a separation of the echo only from a single point target, and does not allow perfect separation of the signals in a scenario with distributed scatterers. The reason for this is that the orthogonality condition is not fulfilled at the presence of arbitrary shifts between the transmit signals. According to the Ambiguity function defined by Woodward (1), ambiguity or energy can be moved in the time-frequency plane but not removed [1]. He defined that the mean-squared error between a known waveform $s(t)$ and its version shifted in frequency and delayed in time should be large for no shift present ($\Delta\tau = \Delta f = 0$) and zero for $\Delta\tau \neq 0, \Delta f \neq 0$.

$$\chi(\Delta\tau, \Delta f_\nu) = \left| \int s(t) \cdot s^*(t - \Delta\tau) e^{-j2\pi\Delta f_\nu t} dt \right|^2 \tag{1}$$

In the MIMO-case this will be a problem for observing surface-scatterers because the plane will be completely filled by every waveform. The planes will overlap and thus a separation is not possible. Thus a drawback in the $\Delta\tau, \Delta f$-plane has to be accepted. However in the next two chapters a solution is introduced with which it is possible to fulfill the ambiguity function using waveforms shifted in time and frequency in combination with digital beamforming on receive.

3. Short-Term Shift-Orthogonal Waveform

To overcome the contradicting requirement described in the last chapter, a novel orthogonal waveform scheme is suggested according to the ideas of [2]. The basic idea behind this approach can be expressed by a restricted orthogonality condition:

$$\int s_i(t) \cdot s_j^*(t - \tau) \cdot dt = 0 \qquad \forall \quad \tau \in [\tau_a, \tau_b] \;\; \text{and} \;\; i \neq j \tag{2}$$

where two different transmit signals s_i and s_j are only orthogonal for a subset of signal shifts τ, which are in this example limited by the interval $[\tau_a, \tau_b]$. This enables a perfect separation of the echoes from neighboring scatterers. A simple example for a suitable waveform is the simultaneous use of mutually shifted and wrapped frequency ramps shown for two transmit waveforms in Fig. 1. In this case channel 1 transmits a normal Up-Chirp, whereas channel 2 transmits a shifted Chirp-Waveform. It can be clearly seen that they are not overlapping in the $\Delta\tau, \Delta f$-plane for scatterers with distances smaller than $c_0 \cdot \tau_p/4$, where c_0 is the propagation speed of the signal and τ_p the pulse duration of the signal. But if a larger surface is observed the plane will be completely filled and the signals will overlap so that they are not orthogonal anymore. This waveform scheme can also be easily extended to more than two transmit signals by dividing the signals in N_{tx} parts, where N_{tx} is the number of transmit channels. In Fig. 2 the impulse response of a point target located at a distance of 150 m can be seen. Due to the chosen pulse duration of $\tau_p = 1$ us the ambiguities will appear at $\pm c_0 \cdot \tau_p/4$ corresponding to 225 m and 75 m respectively with an amplitude 3 dB below the amplitude of the scatterer. However, as already mentioned, by the use of distributed scatterers the ambiguities will be distributed over the whole space and the result will be smeared drastically. In the next chapter a solution for the ambiguity suppression is described.

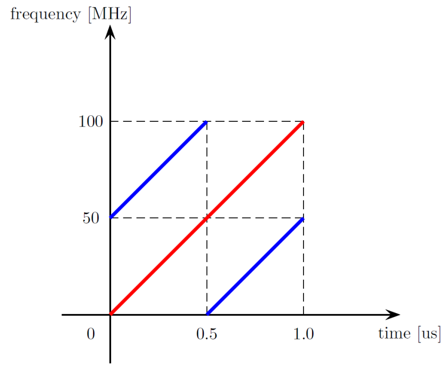

Figure 1: Short-Term Shift-Orthogonal Waveform in the time-frequency-plane.

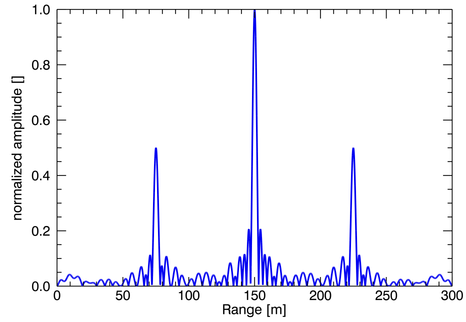

Figure 2: Impulse response of one point target located at 150 m.

4. Spatial Filtering With Digital Beamforming On Receive

To suppress the ambiguities described in section 3 it is suggested to use digital beamforming on receive [2]. Due to the side looking geometry of the radar each scatterer will be seen at a different angle, also called an angle of arrival (AOA). Using the known relation between frequency, time and AOA it is possible to distinguish different transmit signals by applying digital beamforming on receive. In the proposed method, known as Scan-On-Receive (SCORE) [3], an imaging swath is completely illuminated by a wide antenna beam on transmit (Fig. 3), while on receive a narrow high gain beam is following the echo of the transmitted signal on the ground (Fig. 4). In contrast to a system with a single Tx-Rx-channel the gain of such multichannel DBF radar is increased by a factor of $N_{rx} \cdot N_{tx}$, where N_{rx} is the number of receive Channels. Using the multichannel capability and a vailability of digital data from each channel it is possible to optimize the gain for certain directions and furthermore to apply a spatial filtering for suppression of range ambiguities resulting from the restricted orthogonality condition introduced in section 3. After a coherent combination of all channels a range compression is done. However, this method is applicable only for radar systems with a short pulse duration compared to the swath width, e.g. spaceborne SAR systems. If the pulse duration is too long compared to the imaging scene, SCORE can only be used with a prior application of range compression, because otherwise the transmitted pulse will cover the whole swath and, while the antenna beam covers only its portion pointing at a certain direction, this would lead to unacceptably high pulse extension losses. However the use of the proposed waveforms after range compression results in the loss of the information about the receive time of each echo signal and leads to impossibility of an application of a time-variant filtering over the AOA. Thus in this case SCORE technique will not work and, in order to enable its application, the usage of multiple time independent beams looking at different subsequent directions is suggested (Fig. 5). An overlap of adjacent antenna beams is in favor allowing an achievement of better performance. For each beam and receive channel a time-variant filtering and range compression for each transmit signal are to be made. Finally, they are coherently summed up yielding as a result signal free of ambiguities.

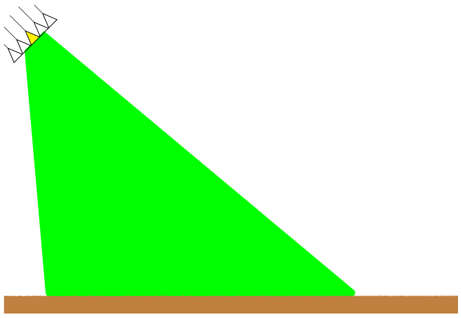

Figure 3: On transmit a wide beam illuminates the swath.

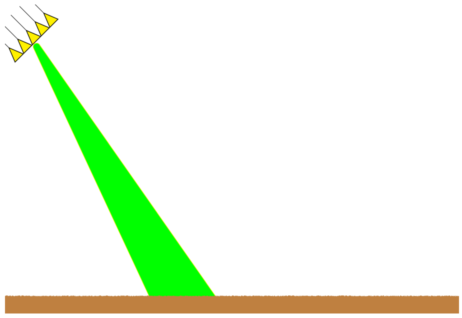

Figure 4: On receive a narrow beam illuminates the swath.

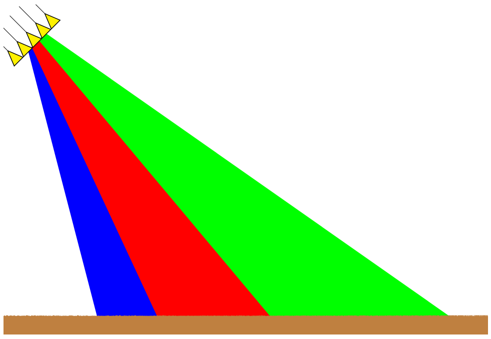

Figure 5: Multiple time-independent beams.

5. MMRS Demonstrator

The architecture of a modular reconfigurable multi-channel DBF radar demonstrator is depicted in (Fig. 6). The purpose of the MMRS demonstrator is to show and verify new techniques and concepts including advanced MIMO imaging systems for the future spaceborne remote sensing applications. The system considered in this paper is configured to operate in X-band using two transmit and eight receive channels. This is the basic configuration, while the demonstrator will later be extended to other frequency bands and more transmit channels. The desired transmit signal is synthesized using an Arbitrary Waveform Generator (AWG) and up-converted to X-band using an RF mixer and an analog signal generator (PSG). The up-converted RF signal is filtered using a bandpass filter, amplified and transmitted. At the receiver part, the echo signals are independently received by each channel, amplified using Low Noise Amplifiers (LNAs), down-converted to the Intermediate Frequency (IF) band, and finally digitized. Data acquisition at each receive channel allows a posteriori combination of the recorded signals to form multiple beams with adaptive shapes. The additional information about the direction of the scattered radar echoes can then be used to suppress spatially ambiguous signal returns, increase the receiving antenna gain and suppress spatially localized interferences. Thus, the MIMO radar incorporates advanced features in addition to High-Resolution Wide-Swath (HRWS) SAR imaging, offering improved imaging performance, and making it possible to acquire more information about the targets. Basis DBF capabilities of this MMRS demonstrator were presented in

[4], where the resolution and the SNR of the radar system in a MIMO configuration could be significantly increased compared to a conventional radar with just a single channel.

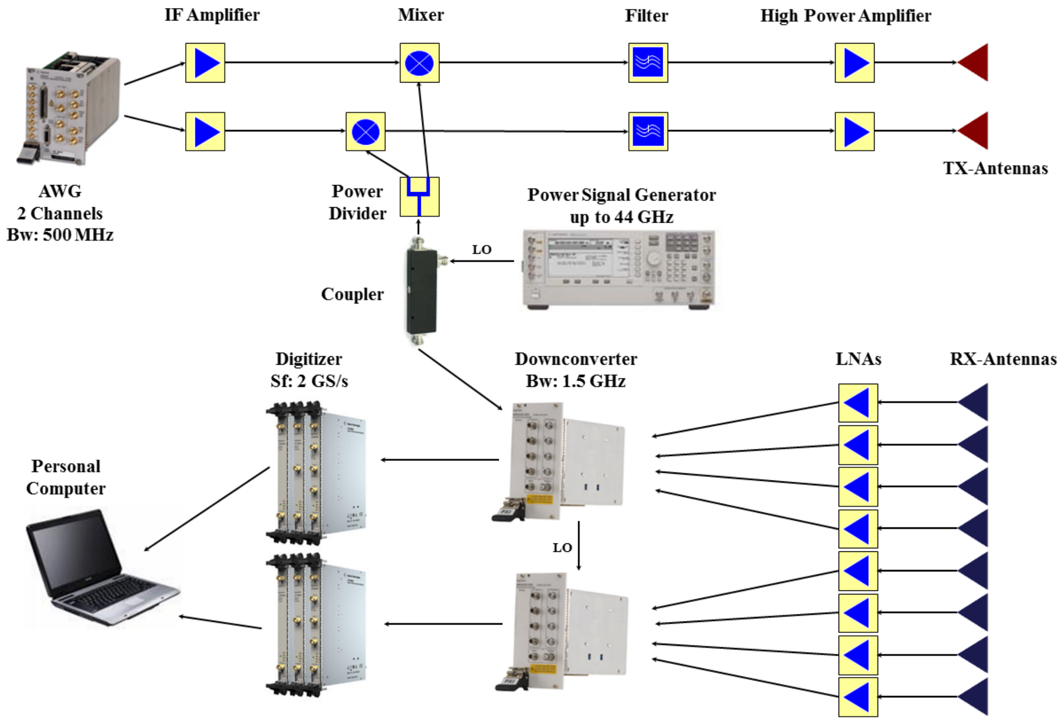

Figure 6: Simplified block diagram of the MMRS demonstrator.

To calibrate the demonstrator a calibration block is inserted directly before the antennas forming a closed loop between transmit and receive channels. This configuration makes it possible to obtain the matched filter function for each Tx-Rx channel pair. Furthermore it is possible to acquire the matched filter signal after every received pulse by fast electronic switching of the calibration before until the radar transmits the next pulse. Using this approach not only constant amplitude and phase errors can be suppressed but also slowly time-varying errors. As the first step before the raw data is processed all channels are synchronized in time and in amplitude by applying a calibration algorithm based on the power density spectrum and matched filtering.

6. Measurements

For the demonstration and verification of the Short-Term Shift-Orthogonal Waveforms with the MMRS demonstrator, an outdoor measurement of the target localization in the range direction was conducted. This measurement was performed with two transmit channels, while on receive a Uniform Linear Array (ULA) with six elements was used. Two corner reflectors representing point targets were placed at a radar slant range distance of 21.5 m and 27.7 m respectively. The transmitted waveforms had a pulse duration of 0.8 us and a bandwidth of 300 MHz resulting in a range-resolution of 1.0 m. The measurements were performed in X-Band at a center frequency of 9.55 GHz. While channel Tx1 was transmitting an Up-Chirp, channel Tx2 was transmitting a Short-Term Shift-Orthogonal Waveform with a shift of $\tau_p/2$ (see Fig. 1). From the obtained results shown in [Fig. 7] it can be seen that the measurement data agree with the theoretical prediction: the ambiguities are located 60 m from the real target with an amplitude 3 dB below the target response. By applying a time-variant bandpass filter (Fig. 8), the ambiguities can be completely suppressed. Due to the small swath width in this imaging scenario a digital beamforming was not necessary.

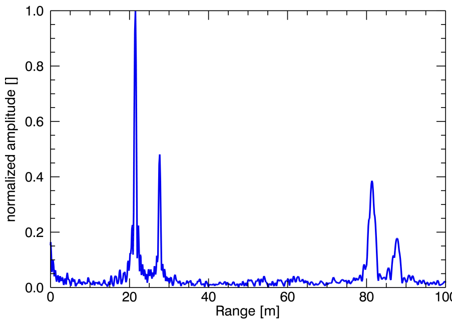

Figure 7: Range compressed data without spatial filtering.

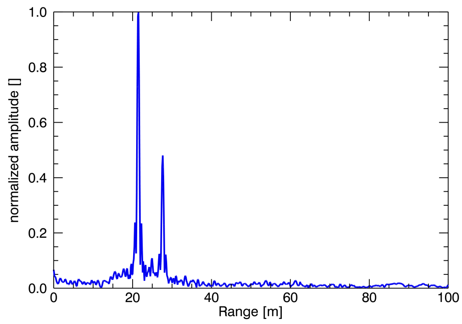

Figure 8: Range compressed data with spatial filtering.

7. Conclusion

An ambiguity function for a radar system was considered and discussed. A new kind of transmit signal for MIMO SAR was introduced with the description of its limitation. After that it was described how to overcome this limitation with the use of DBF on receive. Finally the theoretical aspects were verified with measurements made with the in-house MMRS demonstrator.

The results obtained for the advanced DBF radar demonstrator presented in this paper are the first step in the development of the future spaceborne Multi-Modal Radar Systems, such as MIMO imaging radars using orthogonal waveforms, DBF Synthetic Aperture Radar (SAR), and reflector based DBF systems. The innovative imaging techniques and technologies employed in these systems have the potential to considerably enhance the imaging performance of the future spaceborne radars compared to the state-of-the-art SAR sensors existing today.

References

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