Development of a MIMO Radar System Demonstrator

Calibration and Demonstration of First Results

T. Rommel, A. Patyuchenko, P. Laskowski, M. Younis, G. Krieger
Microwave and Radar Institute
German Aerospace Center (DLR)
81234 Wessling, Germany
tobias.rommel@dlr.de

***Abstract*— Multi-Modal Radar Systems (MMRS) using Digital Beam-Forming (DBF) concept offer higher operational flexibility and improved performance compared to the conventional radar systems using analog beam steering. In particular, Synthetic Aperture Radar (SAR) based on DBF concept overcomes the fundamental limitation of classical SAR systems delivering high resolution and simultaneously wide swath images. This paper presents a laboratory prototype of the next generation MMRS system - a reconfigurable Multiple Input Multiple Output (MIMO) radar demonstrator based on the DBF architecture. The hardware configuration of the demonstrator is described in detail, and the system calibration and signal processing procedures are considered. The first measurement results confirming its functional capabilities are presented and discussed.**

Keywords-digital beam-forming; MIMO; radar;

I. Introduction

The success of current spaceborne Synthetic Aperture Radar (SAR) is boosting the performance requirements of next generation systems. In order to cope with the evolution of SAR the design of the new systems will need to meet higher requirements for spacial and radiometric resolutions and higher coverage. This tendency is recognized nearly independently of the application area and manifests itself through several study programs initiated by space agencies aiming at the design of future SAR systems. A review of several ongoing studies shows that a promising candidate for the next generation SAR systems is a multi-channel radar utilizing digital beam-forming (DBF) techniques [1, 2], which allows to overcome the fundamental high resolution/wide swath limitations of the conventional SAR systems [3, 4].

A prototype of the next generation Multi-Modal Radar System (MMRS) – a reconfigurable MIMO DBF radar demonstrator – is described in this paper. The purpose of the paper is to introduce the hardware architecture of the MMRS radar including the calibration description of the system as a whole, and to present the first measurement results demonstrating the fundamental DBF radar capabilities which open novel possibilities to achieve better performance and higher operational flexibility compared to the conventional radars.

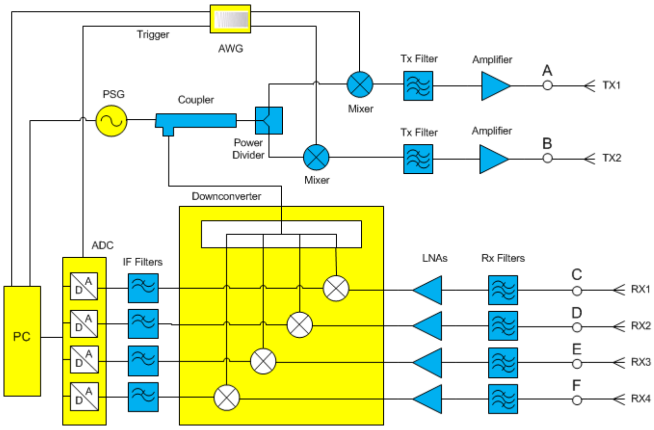

Figure 1. Block diagram of the Digital Beam-Forming (DBF) system radar demonstrator.

The paper starts with the introduction of the MMRS demonstrator system design and its functional blocks. The discussion is followed by the consideration of the system calibration procedure and the corresponding hardware implementation. Afterwards the measurement scenario is introduced and the measurement results are presented and discussed. The paper concludes with a summary.

II. Digital Beam-Forming Demostrator System

The Microwaves and Radar Institute of German Aerospace Center is conducting the research and development of the innovative concepts and advanced operational modes for the future spaceborne SAR systems [5]. The new imaging techniques and technologies have the potential to considerably enhance

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the imaging performance of future systems compared to the state-of-the-art SAR sensors like TerraSAR-X/TanDEM-X, Radarsat-2 or Sentinel-1. In the framework of these activities a modular reconfigurable multi-channel DBF radar demonstrator operating at multiple frequency bands was developed in the Institute. The simplified architecture of the system based on the cPCI form-factor is depicted in Figure 1. This system is configured for the X-band operation using two transmit and four receive channels. This is the basic configuration intended to be used for the first functionality tests, while the MIMO MMRS demonstrator can be further extended up to eight independent receive channels allowing higher operational flexibility.

In the following the basic operational principle of the radar demonstrator is described. At the transmitter part of the system the desired complex chirp signal is synthesized using an Arbitrary Waveform Generator (AWG) and up-converted to the X-Band using an RF mixer and an analog signal generator (PSG). The up-converted signal is filtered with a band-pass filter, amplified and transmitted using a patch antenna. At the receiver part the echo signals are independently received by each channel where they are amplified using Low Noise Amplifiers (LNAs), down-converted to the Intermediate Frequency (IF) band, and digitized. Data acquisition at each receive channel independently 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, to increase the receiving antenna gain, to suppress spatially localized interferences, and to gain additional information about the dynamic behaviour of the scatterers and their surroundings. The main purpose of the suggested DBF radar prototype is to test and develop advanced operational modes for the future spaceborne imaging systems as well as to research their functional capabilities and limitations.

III. Calibration

In order to reduce the measurement uncertainty of the radar system its calibration has to be done. The end-to-end system calibration procedure applied to the DBF radar demonstrator and described in the following treats the entire radar measurement system with all its components and cabling between them as a single entity. It removes the errors introduced from cabling between the components, wiring in the instrumentation front-end, and inaccuracies introduced through the non-linear behavior of the individual system components and antennas themselves. In addition to that the end-to-end calibration allows us to compensate channel synchronization errors and certain instrumentation components errors, such as offset errors.

The above errors introduced in the radar system can be compensated at the signal processing stage by using the matched filter theory [6]. The radar signal processing consists in correlation of the backscattered signal with a reference function or replica. According to the matched filter theory the reference function is the complex conjugate of the time reversed system impulse response. Thus feeding the source signal into the radar demonstrator and measuring the system's response one can obtain the reference function containing system errors represented by the phase and amplitude distortions. This additional information about the errors contained in the reference function allows us to remove them from the backscattered signal during the signals' correlation process.

The radar system end-to-end calibration block is schematically depicted in Figure 2. This functional block, implemented in hardware, is integrated into a compact box embedded into the radar demonstrator enabling an easy end-to-end system calibration by simple electronic switching of the signal path without any hardware disassembling. The integration of the calibration block into the demonstrator is done by connecting the outputs of the DBF radar labeled in the Figure 1 by letters A–F with the corresponding inputs of the calibration box labeled in Figure 2 by letters A'–F'.

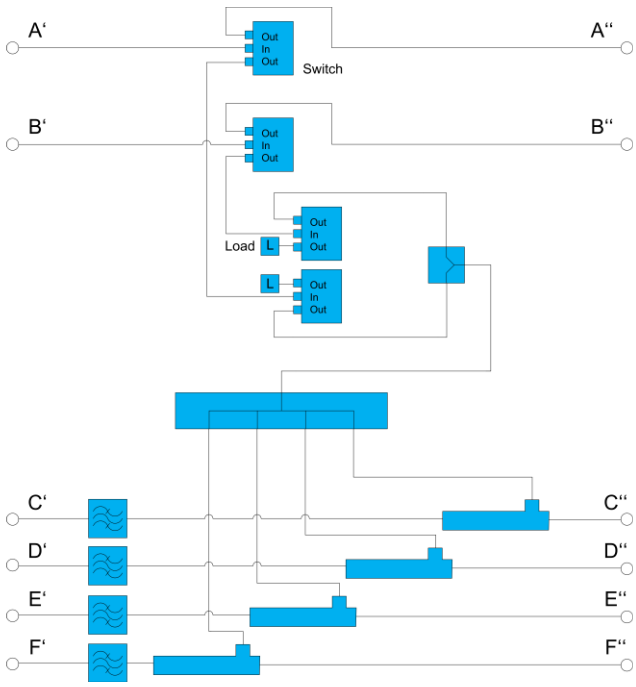


Figure 2. Schematic representation of the calibration network.

The transmit and receive antennas are in turn connected to the outputs of the calibration box depicted in Figure 2 by the letters A"–F". By using this calibration network it is possible to set the two transmit channels into one of the three operational modes: calibration, load or transmission.

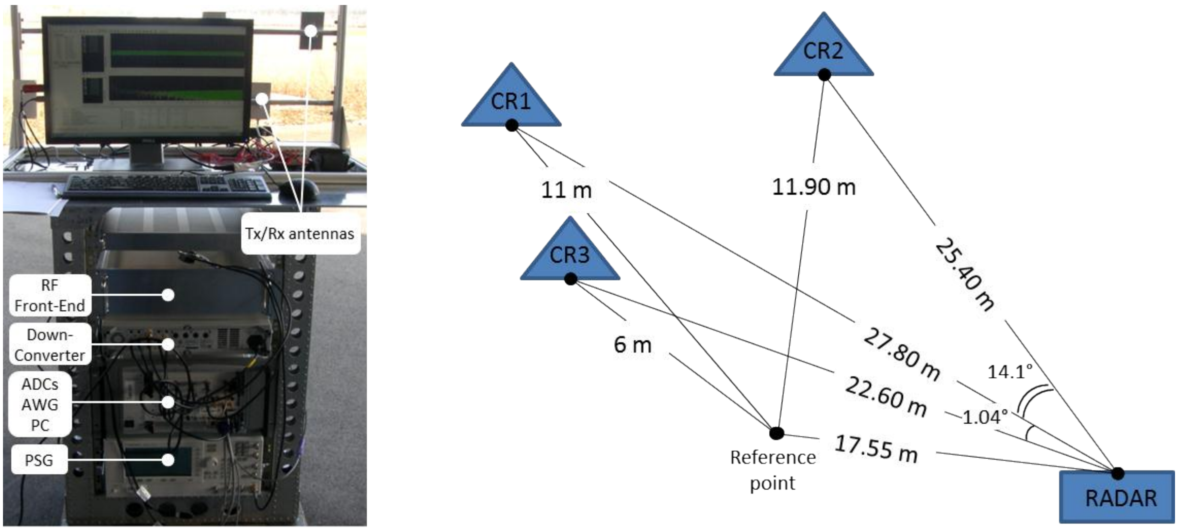
In the “calibration” mode, the corresponding transmit channel is shortened with the receiver using the electronically controlled switching elements. The transmit signal in this case is split over four receive channels and passed through all the receiver’s stages being finally acquired by the digitizer. While one of the transmit channels is set in the “calibration” mode, the other one is always set in the “load” mode meaning that it is loaded with a 50 Ohm impedance. Such architecture allows us to record a reference function for every possible combination of the transmit and receive channels. The signal acquired in this way represents the compensation function which has to be later applied to measurement results in order to correct for system’s errors. When the calibration is done and the compensation function is acquired for every channels’ combination, the radar system is switched into the “transmit” mode in which the signal is lead through the switching components to the transmitting antennas.

The reference signal obtained using this calibration procedure, after its acquisition by the digitizer, will be delayed by the system propagation time corresponding to the length of the internal cables and wires in the radar. While performing the radar measurements, knowing its value allows us to correct the time of arrival of the echo signals and thus precisely determine absolute positions of the radar targets. Furthermore this calibration method allows us to compensate the nonlinearities caused by the radar components. Since this distortion remains mainly constant over time after the cross correlation the major amount of these errors can be eliminated.

IV. Measurement Setup

For the first demonstration of the basis functionality of the DBF radar demonstrator the outdoor measurements of the target localization in the two dimensional plane were conducted. The developed radar system in hardware is shown in Figure 3 (a) with all its main building blocks. The system is controlled using the in-house software written in C and run on the embedded PC installed in the cPCI crate. The measurement scenario setup is depicted in Figure 3 (b). This measurement was performed with a single transmit channel, while on receive a Uniform Linear Array (ULA) with four elements and an inter-element of spacing of 2.8·λ was used.

The measurements were done in three steps. The corner reflector representing a target was successively placed at three different locations CR1, CR2 and CR3 according to the setup geometry depicted in Figure 3 (b). The actual distance between the radar system, the target locations and the reference point, used to find the relative location of targets in 2D plane, was measured. Each measurement was conducted for every target location by acquiring the echo signals by each digital channel. The measurement system parameters as well as the signal parameters are summarized in Table 1. The theoretical range resolution achieved with the radar system using the current configuration amounts to 1 m, while the angular resolution in azimuth to 6.5°. The angular resolution can be improved by using the antenna array with a larger inter-element spacing.



a) b)

Figure 3. DBF radar demonstrator system (a) and the measurements scenario setup (b).

TABLE 1 RADAR AND SIGNAL PARAMETERS

	parameters
Sampling rate	2 GS/s
Waveform	Upchirp 100 MHz – 250 MHz
Bandwidth	150 MHz
Pulse length	10.0 us
Center RF frequency	9.55 GHz
Range resolution	1.0 m (theoretical)
Azimuth resolution	6.5° (theoretical)

V. DATA PROCESSING

For the processing of the acquired raw data a special algorithm, schematically depicted in Figure 4, is used to focus the imaged area in range and in azimuth [7]. The raw data from each channel are combined in a single array, and then the Fast Fourier Transform is applied. The same is done for the replica signal of each channel. Then the raw data and the replica are multiplied and the Inverse Fourier Transform is applied to the result of this multiplication. As a result the range compressed signal, allowing us to estimate the distance between each target location and every digital channel, is obtained. However using only the range compression, all equidistant targets will appear within one range resolution cell, independently of their angular positions. It is the purpose of the angular compression to separate the targets according to their angular position. This is done by focusing the array on each angle of the imaged area by multiplying the amplitudes of the azimuth samples corresponding to the given angle with a complex weighting coefficient. This allows us to relate the intensity of the obtained image to the radar cross section for each angle.

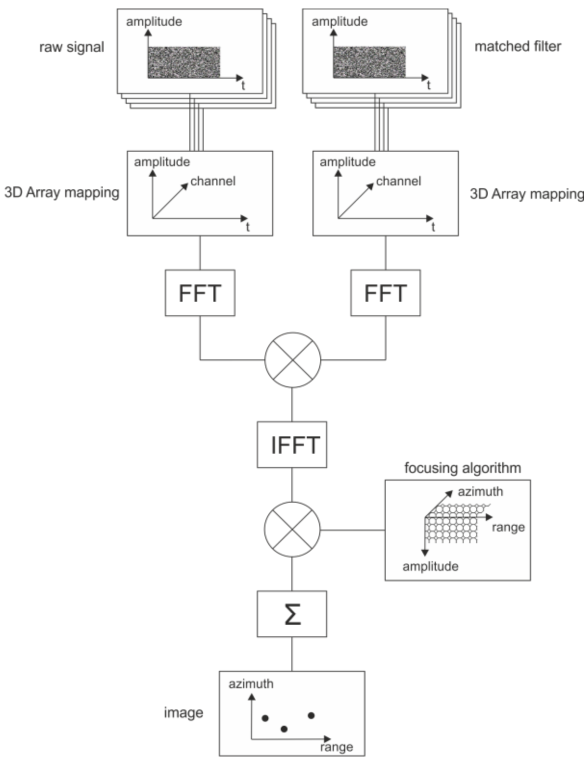


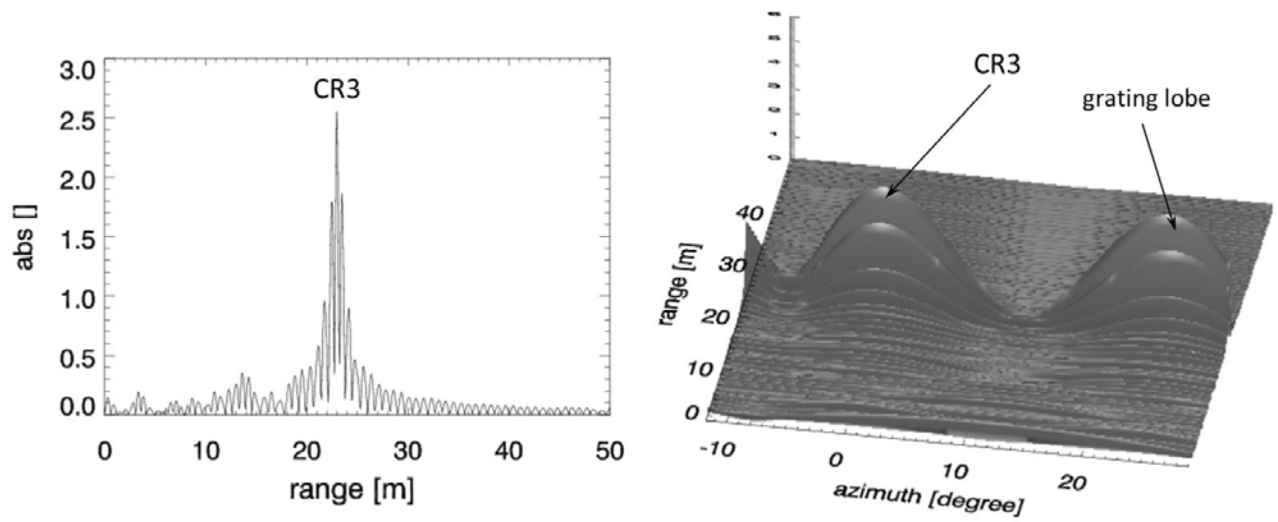
Figure 4. Block diagram of the image reconstruction algorithm.

VI. MEASUREMENT RESULTS

The raw data acquired in the measurement campaign were processed using the above described algorithm. The obtained results are presented in Figure 5 (a) and (b). The Figure 5 (a) shows the range compressed echo signal corresponding to the target CR3 and acquired by a single receive channel. The magnitude of the sin(x) / x function illustrates the response of the corner reflector which is convolved with the transmitted signal as a point target. The maximum at 23 m corresponds to the distance between CR3 and the antenna.

The Figure 5 (b) shows a 3D-plot of the in range and azimuth compressed echo signal corresponding to the same target CR3. The left lobe in Figure 5 (b) is the real response of the target and the lobe on the right represents the first grating lobe. With the maxima of these both lobes it is possible to estimate the target position. According to the chosen axes the target is placed at 23 m and 0°. The maximum in the same range line at 20.9° is the resulting grating lobe. It can be seen that the amplitude of both maxima is equal. The reason for this is explained later in this chapter.

The processed data corresponding to all three target locations is plotted in Figure 6. The results are shown on a 2D plane where the abscissa is the relative angular separation of the targets (relative to the second location) and the ordinate is the range from the radar to the target. In this figure the uncertainty-bars CR1, CR2 and CR3 represent the resolution cells within which the corresponding targets are located according to the measurements; the rectangles represent the location of the grating lobes; and the three dots denote the actual locations of the corner reflector. The processing of the measurement results showed that the grating lobes mirror the targets periodically appearing in the imaged area. This is due to the periodicity of the used focusing algorithm containing the sine and cosine functions. The repetition period of the grating lobes is given by the equation (1):



a) b)

Figure 5. Measured range line for a target CR3 (a) and a 3D image containing the target CR3 and a grating lobe.

$$\psi = \arcsin\left(\frac{\lambda}{\delta y_r}\nu\right) \quad \nu \in \mathbb{Z},\ \nu \neq 0 \qquad (1)$$

where λ is the wavelength of the transmitted signal, Δy_r is the distance between the centers of the antenna elements, and ν is the grating lobes' index. Using the geometry of the chosen measurement setup and the equation (1) with $\nu = 1$, the theoretical angular separation between the grating lobes and the target returns is found to be 20.9° what is in agreement with the experimental results shown in Figure 6.

From the obtained results the ratio error of the range and angle measurements for each target location can be estimated relative to the center of the resolution cell. Its value for the range measurements is acceptable with its maximum by 5.8 %. The ratio error for the angle measurements is however considerably higher reaching 52 % for the angular separation between the targets CR1 and CR3. The discrepancy between the measured and the actual data is due to several factors which can be accounted for the low angular resolution, superimposed random fluctuations in the measurement results, and the limited accuracy of the instrumentation used to define the exact locations of the targets. These factors can be later partly compensated by further system development as well as by using additional calibration methods thus allowing us to reduce the measurements uncertainty to its minimum.

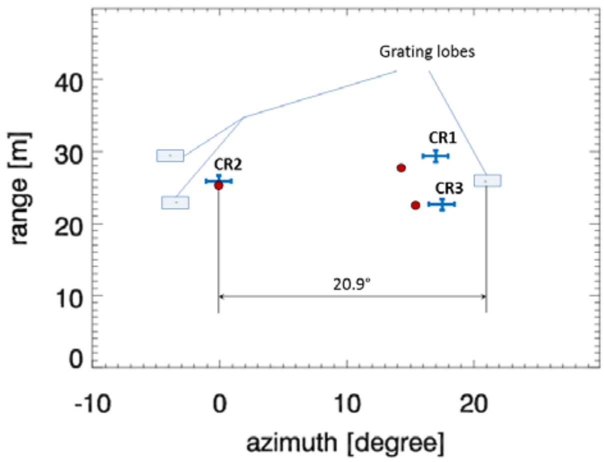


Figure 6. Measurement results of a target localization in a 2D plane using the DBF radar demonstrator with a single transmit channel and four digital receive channels.

VII. CONCLUSION

The advanced Digital Beam-Forming (DBF) reconfigurable radar demonstrator based on the modular architecture was presented together with its system calibration module in this paper. The measurement setup and the algorithm used for the measurement data processing were described. The first experimental results obtained with the DBF hardware demonstrator showed a relatively good agreement with the reference data and the need for further performance improvement.

The performance of the radar demonstrator can be improved by using more receive and transmit channels. The use of several transmit channels with orthogonal signals would enhance the capabilities of the radar by the possibility to employ innovative operational modes considerably enhancing the performance and flexibility of the system.

The radar demonstrator presented in the paper is the prototype of the next generation Multi-Modal Radar Systems (MMRS) which will be able to satisfy the stringent requirements of the future spaceborne remote sensing radars to achieve high resolution and wide coverage of the imaged area.

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.

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