Orthogonal Waveform Experiments with a Highly Digitized Radar

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Abstract

An innovative highly-digitized radar system called GigaRad is currently under development by the DLR Microwaves and Radar Institute. An objective of the system is having a flexible, high-resolution imaging radar with wide-swath or 3-D capabilities, requiring transmission and reception on multiple channels simultaneously. However, a problem in multi-channel systems, especially in the transmit part, is the interference between simultaneously transmitted signals being operated at the identical frequency range. This paper examines the use of orthogonally coded waveforms as a method to overcome the interference between signals sharing the same bandwidth. First measurement results for a few selected waveforms are presented.

1. Introduction

The technological progress in analog-to-digital (ADC) and digital-to-analog (DAC) converters has been substantial in the last years. The increase in both the analog bandwidth of instruments and the speed of conversion has made possible many new applications in radar techniques. Furthermore, conversion from/into digital domain is being pushed closer to the front-end, reducing the amount of analog components to a minimum. This reduces drift and non-linearity effects, thus improving the transfer function of the instrument.

The GigaRad system, currently under development by the DLR Microwaves and Radar Institute, is a highly digitized instrument, whose aim is the generation of high-resolution radar images in inverse synthetic aperture radar (ISAR) mode with 3-D and/or wide-swath capabilities. To fulfill both objectives, the system transmits simultaneously on multiple channels different arbitrary waveforms generated by high-speed DACs, based on the multiple-input multiple-output (MIMO) concept; therefore a high-speed ADC and a wide analog bandwidth are also needed in order to sample properly the received signal. Thus, 3-D images could be generated after processing individually the signals received on spatially separated channels. Wide-swath imaging could be implemented by digital beamforming upon receiving. Such requirements shall be fully addressed by the final Gigarad design approach using multiple wideband output and multiple wideband input channels.

At the current stage, a main problem is the discrimination of the waveforms at the receiver, especially when they share the same bandwidth. However, the use of orthogonally coded signals can overcome this issue. There is an extensive literature on orthogonal signals [1][2][3], and they have found a niche across different technological applications, but their use on radar is still a hot topic of research. In this paper, we examine several signals that, because of their special autocorrelation and cross-correlation properties, promise usage on multiple-channel radar-imaging scenarios. Some first theoretical and experimental investigations have been performed and a few measurement results are outlined next.

2. Outline of the Experimental System Concept

The GigaRad experimental system is based on the heterodyne principle and composed of two transmitting channels and one receiving channel. The transmitted signals are digitally generated by an arbitrary waveform generator working at 10 GS/s. In each transmitting channel, the radar signal is up converted to the X-band, filtered (only the upper sideband is let through), power amplified and fed up to a horn antenna. Upon transmission, the radar signal is scattered off a determinate object. Part of the energy of the transmitted signal reaches the receiving antenna and is low-noise-amplified, down-converted and filtered. Finally, the received signal is sampled by a high-speed sampler. The transmitting and receiving channels are fed by the same local oscillator (LO) in order to perform coherent conversion operations. Because of the high data rate involved in the process and the length of the signal pulses, a high writing speed is needed; therefore the data are stored on a hard drive raid system. A block diagram of the system can be seen in **Figure 1**.

In this preliminary step the system serves two major purposes, which are the verification and validation of theoretical results, and the performance checks of the ADC and DAC devices. In this current configuration two independent arbitrary signals can be generated and transmitted in parallel, and then received by one common receiver. In a first matched filter approach the received sampled signal is finally correlated with a reference pulse by the radar processor.

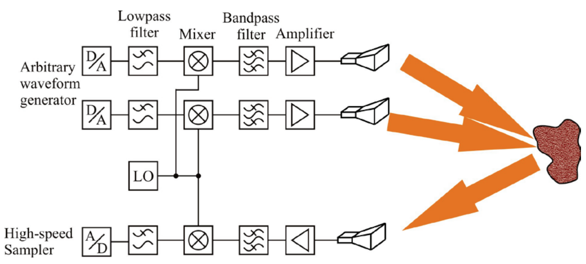

Figure 1 Block diagram of the first experimental realization of GigaRad.

3. Orthogonal Waveforms

As mentioned before, the new digital resources in hardware and software enable the implementation of different waveforms that were before considered unfeasible. There is an extensive literature on the topic of radar waveforms, and a general performance criterion can be drawn, related to the autocorrelation and cross-correlation properties. First, the autocorrelation of the function is wanted to be sharp and to have low sidelobes. The sharpness in the autocorrelation function is related to the bandwidth distribution of the signal, and is translated into high spatial resolution, while low peak sidelobes mean that weak scatterers are not masked by nearby stronger ones. Second, a low cross-correlation level between signals is also very important in a system with several transmitting and receiving channels sharing the same bandwidth. Regarding this criterion, different state-of-the-art waveforms were analyzed and compared.

Initially a linear frequency modulated pulse or 'chirp' was transmitted and received in order to test the basic functionality of the experimental system. Non-linear frequency modulation techniques were also explored, indicating that a small change in the modulation of a radar signal can generate lower sidelobes in the autocorrelation function, but they were discarded since they do not offer orthogonality in a system with more than two transmitting channels.

The ideal orthogonal signal is a pure white Gaussian noise, with an autocorrelation represented by the Dirac delta function and zero cross-correlation level, but this is only valid for the infinite bandwidth case. However, it has been proved in literature [4] that bandlimited Gaussian noise signals can achieve high cross correlation suppression. The flat spectrum provides also an almost ideal frequency response, but the shape of the frequency window determinates the sidelobes of the autocorrelation function. Using a rectangular window as shown on **Figure 2** results in the highest spatial resolution, but fixes the sidelobe peaks around -13 dB, which is the same level as obtained by a linear chirp.

Another technique that improves the signal autocorrelation function while at the same time achieving low cross-correlation level is phase coding, which consists on dividing a long pulse into sub-pulses or bits of identical duration with a different phase applied to each bit, following a given code sequence. The code sequence is then specially chosen to minimize the peak sidelobes in the autocorrelation function. This type of signals comprises polyphase codes such as the Frank code, which can be extended in length by adding more phase steps and therefore achieve lower correlation levels. However, not all polyphase sequences present orthogonal properties and there are also practical implementation difficulties due to the high number of phase steps.

Pseudonoise sequences combine the versatility of phase codes and the random appearance of the Gaussian waveform. They are binary sequences easy to generate and are used extensively across different technologies. It was determined in [5] that there are "preferred pairs" of codes among these sequences, which yield the lowest possible cross-correlation level, called Gold sequences. For each pseudonoise sequence of length M, there are $M + 1$ "partners" of the same length that fulfill the Gold sequence property. A detailed explanation of how to practically generate the Gold sequences can be found in [3]. For their use in radar, the binary phase sequence is represented with individual bits of phase equal to 0 and π respectively, which modulate a carrier. For the experiments with the GigaRad system, the frequency spectrum of the Gold sequence was band-limited by a sinc-weighting interpolation method described in [6], and the resulting curved spectrum is shown in **Figure 3**. This spectrum shape yields higher side lobe suppression but worse spatial resolution.

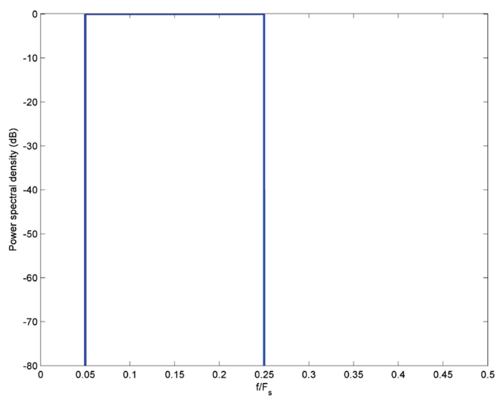

Figure 2 Frequency spectrum of the band limited Gaussian noise transmitted signal normalized to the sampling frequency.

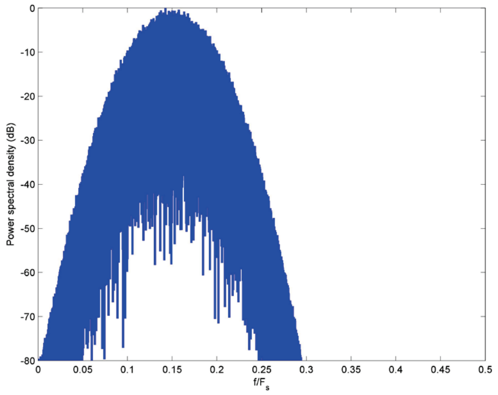

Figure 3 Frequency spectrum of the band limited Gold coded transmitted signal normalized to the sampling frequency.

4. First Measurement Results

In a theoretical and numerical analysis various waveform types have been investigated with respect to their auto- and cross-correlation performance [1][2][3]. This is necessary for achieving sufficient discrimination of the multiple transmit signals being received simultaneously in the same receiver. Because of their promising behavior, the Gaussian noise and the Gold sequence were selected as waveforms for the radar measurements. The Gaussian noise signal was chosen because of its flat spectrum, low cross-correlation level and low probability of intercept; and the Gold sequences by reason of random appearance, low autocorrelation sidelobes and low cross-correlation level. Gold sequences present also a more uniform envelope level than Gaussian noise waveforms and they offer the possibility to transmit information.

Having chosen what to transmit, the system was mounted as a test setup on the roof of a building and the transmitting antennas were symmetrically arranged beside the receiving antenna, looking down to the target scenario. The transmitted signal bandwidth was set to 2 GHz for the noise signal. The effective bandwidth achieved by the transmitted Gold coded signal was much less (around 800 MHz) as can be observed in **Figure 3**.

The initial measurement consisted on the range profile of a single corner reflector located at about 28 m distance from the sender. In this measurement an orthogonal reference code is assigned to each channel and the signals are transmitted by the two antennas. The received signal is subsequently correlated with the reference codes. This is shown in **Figure 4** for the case of the Gold sequence (top) and for a Gaussian noise waveform (bottom).

The correlation of the received signal with the corresponding transmitted waveform shows a sidelobe suppression of more than 20 dB for the Gold sequence (**Figure 4**, top, in red), whereas the Gaussian noise waveform presents the expected typical sinc-shape with a side lobe suppression of 13 dB and a high spatial resolution (**Figure 4**, bottom, in red).

However, the more interesting result for this study is shown on both graphs by the blue line. The correlation level with the non-corresponding waveform is kept 40 dB below for the Gold sequence and 50 dB below for the Gaussian noise. This result can be extended not only to the pair sequence but to a signal with an entire different coding, leaving room to even more combinations of orthogonal signals. Although not yet completely optimized, the measurement results reflect a high enough discrimination for many radar applications, which can be additionally improved by using longer sequences and more refined processing.

The discrimination of a corner reflector in the range profile measurements reflects only a part of the main measurement mode, the ISAR constellation. In order to proof the capability to generate two independent two-dimensional images at the same time by means of transmitting the orthogonal waveforms, a more complex scenario was set on a rotating platform. The relative movement between the fixed sensor and the rotating target is similar to an air- or space borne synthetic aperture radar sensor in a spotlight mode.

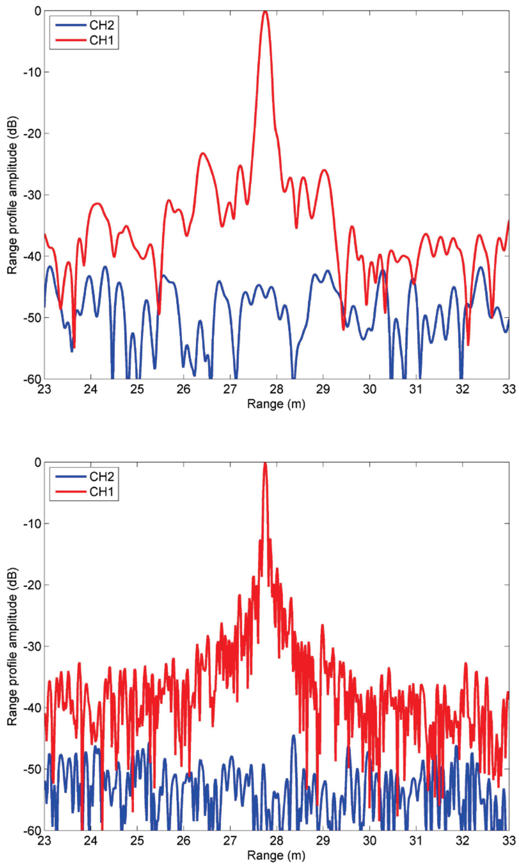

Figure 4 Measured X-band impulse responses (range profiles) of a corner reflector. The received signal was correlated with both reference codes. Top: Gold sequence, bottom: Gaussian noise.

This second scenario consisted on five corner reflectors. Each corner had a radar cross section (RCS) of 0 dBm^2 and they were placed on the tips of 50 cm equilateral triangles, so there was a distance of 50 cm between each target. The reconstruction of the scenario for the main direction is shown in **Figure 5**. In this case, two orthogonal Gold coded waveforms were transmitted and the reconstruction was performed for a single channel with a matched filter approach. The five reflectors are reconstructed in the correct positions and most of the sidelobes and clutter is -30 dB below.

The proof of the system concept with two simultaneously transmitted signals is shown in **Figure 6**. The position of the rightmost corner reflector was reconstructed for different azimuth observation angles. The observed position of the mentioned target was marked for each channel by a different symbol. The different observation angles caused by the antenna arrangement results in a different position of the main RCS peak, as solved for each signal. The differences proof the potential of coded signals for the use in an ISAR system.

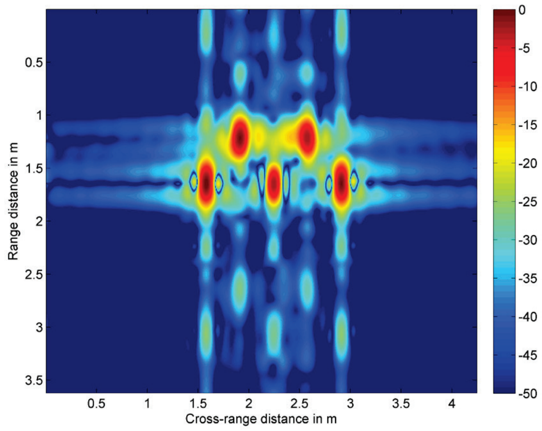

Figure 5 ISAR reconstruction of an artifactual scenario of five corner reflectors arranged on the rotating platform.

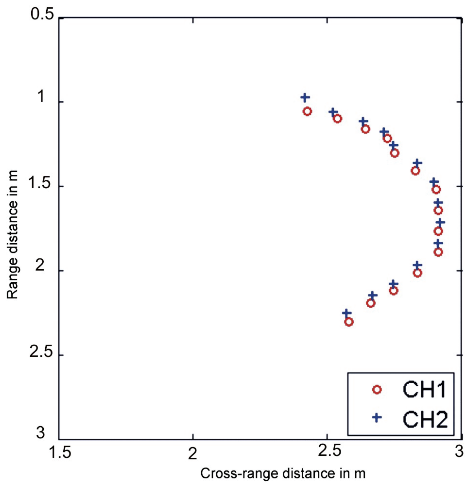

Figure 6 Reconstructed position of one corner for different observation angles.

5. Conclusions

According to their properties, the Gaussian noise and the Gold sequence were selected as waveforms for the radar measurements. The flat spectrum and low cross-correlation level were the main reasons why the Gaussian noise signal was chosen; on the other hand, Gold sequences were chosen because of their random appearance, low autocorrelation sidelobes and low cross-correlation level.

The measurements realized with the experimental system GigaRad on different scenarios demonstrated the main concept of simultaneously transmitting channels in a basic constellation of two transmitting and one receiving channel. We showed that the different waveforms can be discerned at the receiver, with considerable cross-correlation suppression, as observed for the range profile measurement of a corner reflector. The successful reconstruction of a scenario in an ISAR mode proofs that the developed system can be used in future advanced applications such as MIMO, a digital beamforming or a 3D constellation.

Future work foresees expansion into more receiving channels and the inclusion of calibration loops in the final design. The use of orthogonal frequency division modulation (OFDM), which has the advantage of a constant signal envelope in comparison to coded signals, is also a topic to be considered in future developments.

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