GigaRad – a Multi-Purpose High-Resolution Ground-based Radar System

System concept, error correction strategies and performance verification

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Abstract*— Recently DLR has developed and constructed a new experimental radar instrument for various applications like radar signature collection, SAR/ISAR imaging, motion detection, tracking, etc., where high performance and high flexibility have been the key drivers for system design. Consequently a multi-purpose and multi-channel radar called GigaRad is operated in X band and allows an overall bandwidth of up to 6 GHz, resulting in a theoretical range resolution of up to 2.5 cm. Hence, primary obligation is a detailed analysis of various possible error sources, being of no or less relevance for low-resolution systems. A high degree of digital technology enables advanced signal processing and error correction to be applied. The paper outlines technical main features of the radar, the basic error correction strategy and illustrates some first imaging results.

***Keywords*—multi-purpose, multi-channel, SAR, ISAR, high-resolution, MIMO, radar**

I. Introduction

Since the invention of radar by Christian Hülsmeyer more than 100 years ago many new radar systems were and are built with increasing tendency in all areas of remote sensing. The common trend for new systems is toward better performance in polarimetric and radiometric accuracy, sensitivity, operational mode complexity and of course the spatial resolution. To understand and analyze degrading effects for such future new systems, which become important due to the increase in complexity and performance, corresponding ground-based experiments are helpful. Besides exploring new imaging and signal processing techniques the new system GigaRad was developed and constructed at DLR to allow the investigation of these topics.

GigaRad is an experimental platform for exclusively ground-based measurements. In its basic modes the system works as pulse radar at a center frequency of 11 GHz with an instantaneous bandwidth of maximum 6 GHz, allowing the creation of high-resolution range profiles with a theoretical range resolution of 2.5 cm. By the use of an ultra-stable oscillator the system is able to work as a Synthetic Aperture Radar (SAR), or alternatively in an Inverse Synthetic Aperture Radar (ISAR) mode to achieve a similar resolution in azimuth direction. To address many operational modes the system is designed as a multi-channel configuration. In the basic setup two transmit (TX) and two receive (RX) channels for simultaneous operation are constructed, but the system can be extended to any number by using a switch matrix. In the basic mode investigations on MIMO (Multiple Inputs Multiple Outputs) techniques as well as research on orthogonal waveforms or fully-polarimetric signature measurements for instance are possible.

Another interesting mode is a bi-static constellation, separating TX and RX antennas by up to several tens of meters. The basic radar hardware and the displaced TX power amplification, as well as the low-noise RX section are then connected via an optical fiber enabling broadband low loss transmission of the RF signals.

The high degree of digitization and the overall high performance enables a wide variety of applications. A detailed description of the instrument, the error correction strategy, and some illustrative measurement results are presented next.

II. System Description

Obviously the high degree of flexibility results in a very complex block diagram for the instrument. For basic understanding a simplified block diagram is shown in Figure 1. The main functional parts of the instrument are:

- Arbitrary waveform generator,
- IQ transmit part,
- IQ receiver part,
- High-speed data acquisition,
- Error correction network.

Purely digital signal generation is performed using a high-performance arbitrary waveform generator, providing a maximum data rate of up to 10 GS/s. This allows required flexibility on TX side in order to perform simultaneously transmitted orthogonal waveforms as useful in multiple-input multiple-output (MIMO) applications [1] as well as an advanced error correction strategy. Both output signals are coherently generated and fed to the IQ modulator. Then the signal is amplified, filtered, and transmitted. On the RX side the functional concept is the same, except the signal conditioning part before digitization. The main restricting factor for the maximum system bandwidth is the high-speed analog-to-digital converter device providing a sampling rate of

8 GS/s. Hence, in order to fulfill the Nyquist criterion with some safety margins, the maximum analog IF bandwidth is 3 GHz which is the same as the analog 3 dB bandwidth of the input RF section of the digitizer.

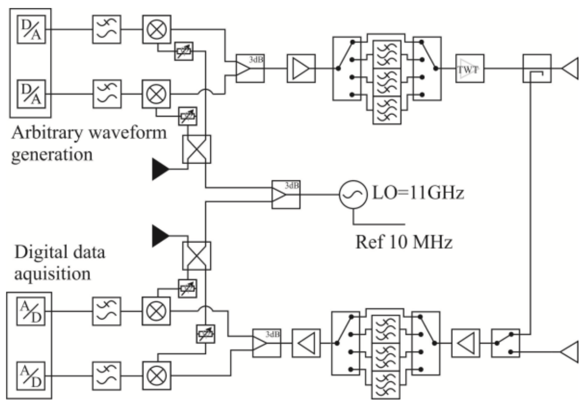


Fig. 1. Simplified block diagram of the GigaRad instrument.

In order to generate technically the maximum bandwidth of 6 GHz, the overall bandwidth is split in an upper sideband (USB) and a lower sideband (LSB) around the center frequency of 11 GHz. A frequency plan of the radar system is depicted in Figure 2. By that means the maximum IF bandwidth only has to be 3 GHz in order to achieve a maximum RF bandwidth of 6 GHz by frequency conversion. However, that procedure requires proper rejection of the image frequency. In order to maintain a maximum system flexibility the image rejection is realized in two different ways. On one hand a group of filters in the RF section of TX and RX modules allows the direct suppression of the USB or LSB, respectively. On the other hand an IQ modulation (mod) scheme for TX and an IQ demodulation (demod) scheme for RX is implemented. Especially the IQ procedures require proper error correction to achieve the desired image rejection as described in section III. Another very important issue for very high-resolution SAR applications is the sufficient coherence and therefore the stability of the local oscillator. In case of GigaRad the implemented phase-locked source offers excellent phase noise and spurious performance and can be additionally locked on an ultra-stable oscillator connecting both the digital and the frequency conversion sections.

Since the instrument is built as a multi- channel system, the RF parts of the TX and RX sections are implemented twice. The currently implemented state enables either radar operation at 3 GHz bandwidth with full two-by-two channels and 6 GHz bandwidth by pulse-to-pulse channel switching [5]. The basic hardware setup is shown in Figure 3. From bottom to top the single units are arranged in a 19´´ rack. The high-power and low-noise amplification sections are excluded to allow a bi-static operation via optical transmission, so they are not visible in Figure 3. Due to the complexity of the system, the different filter constellations, the error correction, and the required timing accuracy, an Erasable Programmable Logic Device (EPLD) and a micro controller are used to control the whole instrument. That unit is currently under development as well as the displaced TX and RX parts.

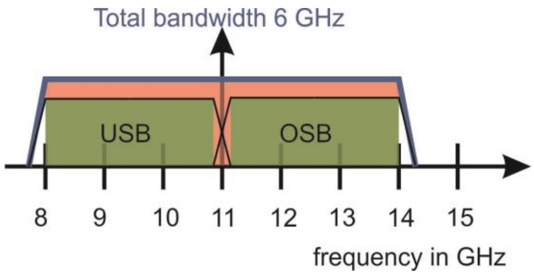
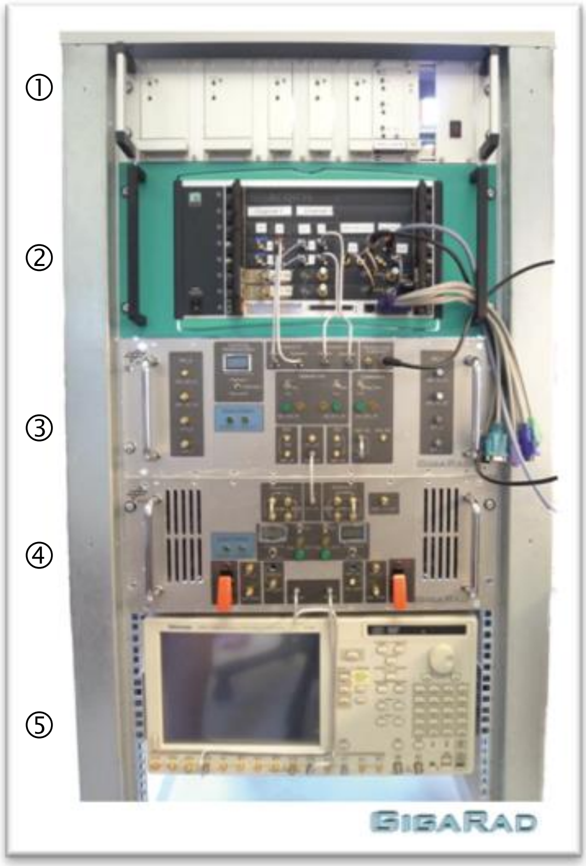


Fig. 2. RF frequency plan of the GigaRad system.



① Supply voltage module,
② High-speed digitizer and data storage,
③ RX signal conditioning module,
④ TX signal conditioning module,
⑤ Arbitrary Waveform Generator (AWG).

Fig. 3. Basic hardware setup of GigaRad.

III. Error correction strategy

As described in section II proper rejection of image frequencies is necessary for high quality images. Therefore in a first step the error correction for the IQ sections is necessary. The instant high IF bandwidth suggests an image rejection concept using connector based components. The drawback here is the higher effort in accounting for the different components. In Figure 4 the main strategy is illustrated. First of all the local oscillator signals are adjusted with manual phase trimmers to exactly 90° phase difference at the mixer diodes of TX and RX sections (blue path). This step is the only one where external hardware is needed. Both IQ sections for TX and RX are operated in this step as down converters, which is possible due to the given reciprocity of the mixer devices. For the determination and trimming of phase and amplitude error, an external signal now is connected at the mod/demod summation port of TX and RX section (right ends of green paths). Then this signal is analyzed at the left ends of green paths in TX and RX section using an oscilloscope, and the phase trimmers are adjusted accordingly.

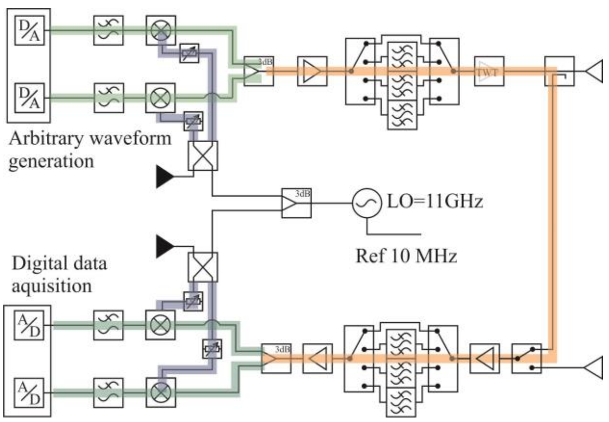


Fig. 4. System correction strategy a) grey: phase adjustment for the local oscillator signal in IQ modulation and demodulation, b) green: amplitude and phase correction of the mod/demod sections, c) orange: amplitude and phase correction of the overall path

In a second step I and Q paths are aligned separately using the different filters for the USB and LSB (green path). Since the signal is sufficiently rejected in the unwanted frequency range by the filters, only one channel of the arbitrary waveform generator has to be used to compare the sampled signals in I and Q channels for amplitude and phase differences. The signal is thereby routed through the calibration path including the coupler right before the transmit antenna and the switch before the receive antenna. A similar procedure is used for proper alignment of both AWG output channels.

In a third and last step the overall frequency response in TX and RX chain is aligned with respect to phase, group delay and amplitude (orange path). Due to the high relative and absolute bandwidth of 54% or 6 GHz the accumulation of the variations of all devices results in a maximum amplitude difference of more than 10 dB. Hence, in a final version of the instrument, an additional equalization filter is intended to reduce the bulk of amplitude variation for smoother signal-to-noise ratio variation over frequency.

Finally, again due to the large bandwidth, the antennas have to be considered. To achieve similar resolution in range and azimuth direction by SAR imaging, the azimuth observation angle has to be in the order of 30°. Therefor in a Scan-SAR measurement the antenna pattern has a significant impact on the image amplitude distribution and has to be corrected for by an appropriate antenna model. Additionally the frequency dependent antenna gain differs considerably for the wide frequency range. Hence, external calibration with a well-known reference target can compensate for that and provide the absolute radar cross section (RCS) for the image. As well the use of an equivalent RCS [4] might be of interest.

IV. Measurement Results

Experimental verification of the GigaRad radar with respect to imaging capabilities and error correction was done by ISAR measurements on a tower-turntable arrangement as shown in Figure 5. TX and RX antennas are arranged at an elevated position and the range distance between radar antennas and turntable was measured to 13.8 m. The incidence angle for that constellation is about 38°. For TX signal a linearly frequency modulated up-chirp using a bandwidth of 6 GHz has been selected in order to obtain range profiles at highest possible resolution. As mentioned earlier the azimuth observation angle has to be chosen to about 30° for similar resolution in range and azimuth direction.

The basic instrument characteristics and the performance of the correction scheme were demonstrated by ISAR imaging of a trihedral corner reflector of 12 cm edge length as shown in Figure 6. In the upper image the uncorrected point source response shows a very asymmetric behavior especially in range direction, which is even more visible in the range cuts in Figure 7. Also the first sidelobes at around -5 dB are much too high as compared to the theoretical value of -13 dB. Even more severe the range resolution is degraded roughly by a factor of 2. Using now the previously described correction method, the point source response shows a spatial resolution of 2.17 cm and sidelobe suppression of about 10 dB. This still differs from theoretical values 2.5 cm and -13 dB, but corresponds with the true transmitted spectrum having a band gap of 300 MHz around the center frequency due to technical reasons, as simulations of that situation have shown.

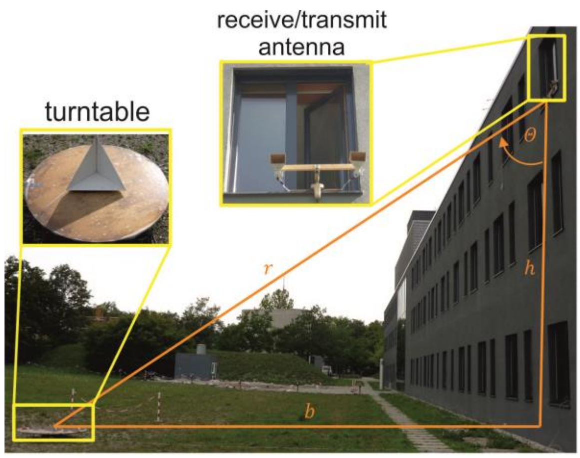


Fig. 5. Measurement configuration of the tower-turntable arrangement used for ISAR imaging.

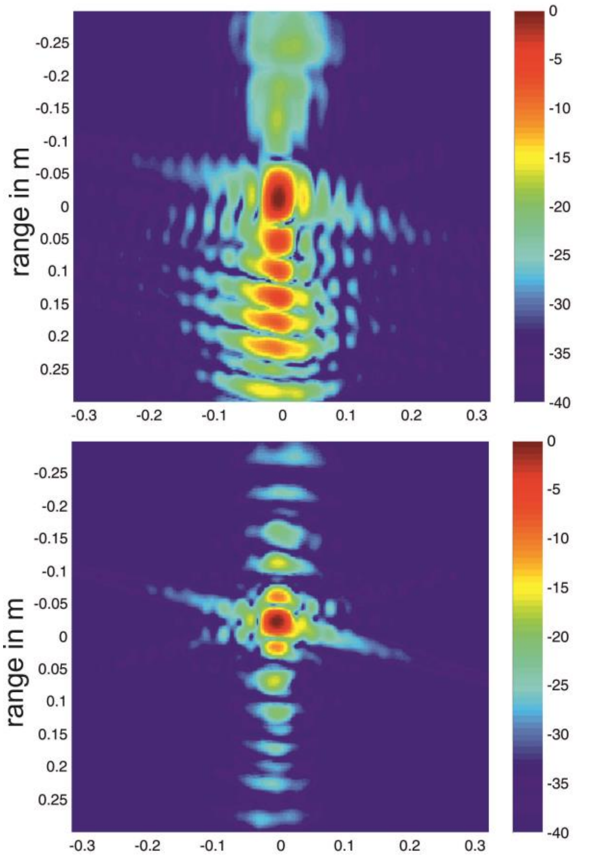


Fig. 6. Normalized logarithmic ISAR image of a trihedral corner reflector. Top: uncorrected response based on raw data; bottom: ISAR image after applying corrections.

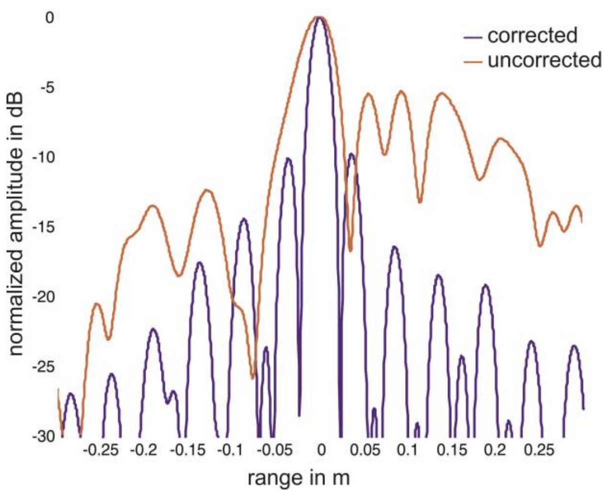


Fig.7 Range cuts through the maxima of Figure 6.

V. Conclusion

In this paper the new multi-purpose and high-resolution ground-based radar instrument GigaRad operated in X band was presented. The very broadband system characteristics, the flexible setup and the multi-channel capability allow a multitude of applications. In order to achieve the expected high performance, the system has been extensively characterized and an appropriate error correction scheme has been implemented. In the paper the performance has been exemplarily shown by ISAR imaging of a point source.

However, it should be mentioned that there are still some challenges to be solved adequately like the huge amount of data and the very high data rate generated for a single image due to the high degree of digitization. Furthermore, the true capabilities of using multiple channels still have to be explored.

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