

RESEARCH PAPER

Design and validation tests for compact FMCW C-band Analog-Front-End for radar imaging applications

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This paper presents the design, implementation, and validation tests of a C-band analog-front-end (AFE) for the frequency modulated continuous wave (FMCW) radar. The system was designed to be used in various radar applications, including short range mode, synthetic aperture radar (SAR) and moving target indication (MTI) mode. The AFE presented here was based on commercial off-the-shelf radio frequency components, and designed as a homodyne system, so the final applications were based on the FMCW radar. Validation tests and experiments were carried out in the laboratory and in open-air environments. The authors present tests of the AFE, including MTI and SAR trials, conducted using a ground moving platform (a car) and an airborne platform (a small aircraft). The results are discussed with the prospect of future work and further improvements in mind.

Keywords: SAR, ISAR, FMCW, RADAR, AFE, RF FRONT END, UAV RADAR

Received 25 November 2015; Revised 11 April 2016; Accepted 18 April 2016; first published online 15 June 2016

I. INTRODUCTION

Radar sensors have become more and more common in everyday life over the years. Although radars were originally designed to monitor military and civil air traffic, their application area is now much wider and more versatile. For example, radar sensors can be found installed in cars to assist in increasing driver safety, but also in bathrooms to control water valves. While radar sensors are fairly well-developed at present, this technology is still rapidly developing, and engineers are constantly searching for the most cost-effective solutions required by the mass market. The wide availability of radio-frequency and digital components in the market makes it possible for amateur radio enthusiasts and/or students to construct simple, low-cost radars. Further, as the drone market has been growing quickly, of late there is an urgent need to equip the drones with small, light radars used as both safety and anti-collision sensors, as well as imaging ones providing ground imaging in dark, foggy or cloudy environments.

The idea of constructing a small radar for drone applications has thus attracted the attention of the authors. This paper presents the design of a frequency modulated continuous wave (FMCW) analog-front-end (AFE) for radar imaging applications. The AFE is an electronic device typically placed

between the digital part of the radar and its antennas. In modern radars the transmitted signal is synthesized digitally and converted to an analogue signal by a digital to analogue converter (DAC). Usually, DACs produce either baseband or intermediate frequency (IF) signals, which are first up-converted in frequency, amplified by an AFE, and then transmitted by a T_x antenna. The signal received by the R_x antenna (or a set of antennas) is amplified by low noise amplifiers, down converted (in the AFE) and then converted again to a digital form using the analogue to digital converters (ADCs). The digital signal is processed in field-programmable gate arrays (FPGAs) and computers to obtain final results in the form of plots, tracks or radar images. At present, the digital components are highly flexible, so it is easy to build radar exciters (radar signal generators) and radar signal processors using commercial off-the-shelf (COTS) components. However, the construction of an AFE is still a challenge as it should be very sensitive and as noiseless as possible on the one hand, but it is highly dependent on the applications on the other hand [1].

In this paper, the authors present a simple project of a wideband AFE for an FMCW radar working at the central frequency of 5.5 GHz with a maximum instantaneous bandwidth of 0.5 GHz, capable of providing detection and high resolution imaging capability (image resolution $15 \times 30 \text{ cm}^2$). In section 2 the concept and description of the AFE hardware is presented. In section 3 the concept of the FMCW radar system with the designed AFE hardware is presented. In section 4 the test results are shown, starting with the laboratory test and ending with the airborne tests and synthetic aperture radar (SAR) imaging.

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II. HARDWARE DESCRIPTION

The goal of the presented work was to design a small, flexible radar with an AFE for an FMCW wideband radar. For this purpose, the central frequency of 5.5 GHz was selected with an instantaneous bandwidth of up to 0.5 GHz. The design was based on COTS. The digital part of the radar was based on software radio modules and a micro PC computer.

The whole idea of the radar signal synthesis and radar signal acquisition and processing can be described in a few steps:

1. The radar sounding signal is synthesized at a low IF frequency by the direct digital synthesis [2] module, which was built using software defined radio (SDR) architecture applied in universal software radio peripheral (USRP) (www.ettus.com). A USRP device baseband frequency of 460 MHz was selected with an instantaneous bandwidth from 10 to 40 MHz.
2. The IF signals are passed via a frequency multiplier network to obtain the central frequency of 5.5 GHz. In the project the frequency multiplier of $12 \times$ was used.
3. The sounding signal is amplified and transmitted by the T_x antenna.
4. The signal received by the R_x antenna is amplified using a low noise amplifier and mixed with the transmitted signal to obtain a 0 IF frequency beat signal.
5. The beat signal is amplified, filtered, and converted to a digital form using the ADC. The USRP device is used as an acquisition system.

The principle of FMCW AFE operations is presented in Fig. 1.

The transmitted signal is a Linear FMCW signal. The fundamentals of the FMCW radar can be found in [3]. The saw-

tooth signal as presented in Fig. 1 can be described by equation (1):

$$s_t = A_t(t)e^{j\phi(t)}. \tag{1}$$

The phase for the FMCW radar is a square shaped function, which can be described for the time of one period $0 < t < T_{chirp}$ as follows (equation (2)):

$$\phi(t) = \frac{B}{2T_{chirp}}t^2 + \left(f_c - \frac{B}{2}\right)t + \phi_0. \tag{2}$$

The received signal is an attenuated copy of the transmitted signal shifted in time and in Doppler frequency (equation (3)):

$$s_r = A_r(t - \tau)e^{j\phi(t-\tau)} * e^{j2\pi f_d t}. \tag{3}$$

After mixing both the transmitted and received chirp signals in the AFE, the 0 IF signal is obtained. The output of the mixer has many frequency components, with the most interesting being produced at low frequencies. The output of the mixer is filtered out with a low-pass filter and amplified. One of the products at low frequencies is a beat signal with a frequency representing target distance (for a stationary object) and target radial velocity with respect to the radar (for a moving object). The beat signal, which is the output of the AFE, can be described as follows (equation (4)):

$$s_{if} = A_{if}(t)e^{j2\pi f_{if}t}. \tag{4}$$

The beat signal frequency is the sum of two frequency factors: one corresponding with target range, the other with target velocity as described by equation (5):

$$f_{if} = \frac{B}{T_{chirp}} \frac{2R}{c} \pm \frac{2v_r}{c} f_c. \tag{5}$$

The AFE system was designed and constructed by the authors solely using hardware available at the laboratory, which was only one of the constraints that had to be taken into account.

The input signal for the AFE was generated by the USRP device at the carrier frequency 460 MHz with a maximum bandwidth of 40 MHz and a maximum power of 0 dBm. The maximum power of the beat signal for the receiving USRP was 10 dBm, and the resolution of 16 bits gave a lower power boundary of the beat signal at the -86 dBm level. Because of this, the gain in the receiver part was set at the level of 40 dB. The transmit power in C-band was designed to be 0 dBm with the possibility of it being increased up to 20 dBm with an external amplifier.

Moreover, the authors took into account the common difficulties in FMCW radars such as coupling, leakage, and filtering unwanted components of the signal, while trying to maximize the performance of the FMCW radars [4] as well as placing particular importance on the transmitted bandwidth and the dynamic range.

A frequency multiplier with a multiplication factor of 12 was used to achieve the desired C-band (carrier frequency of 5.52 GHz) of operation, with a maximum bandwidth of the transmitted signal up to 480 MHz in order to have a range resolution of 0.3 m [5]. The frequency multiplier provides a minimum of 30 dB of attenuation of other harmonics in

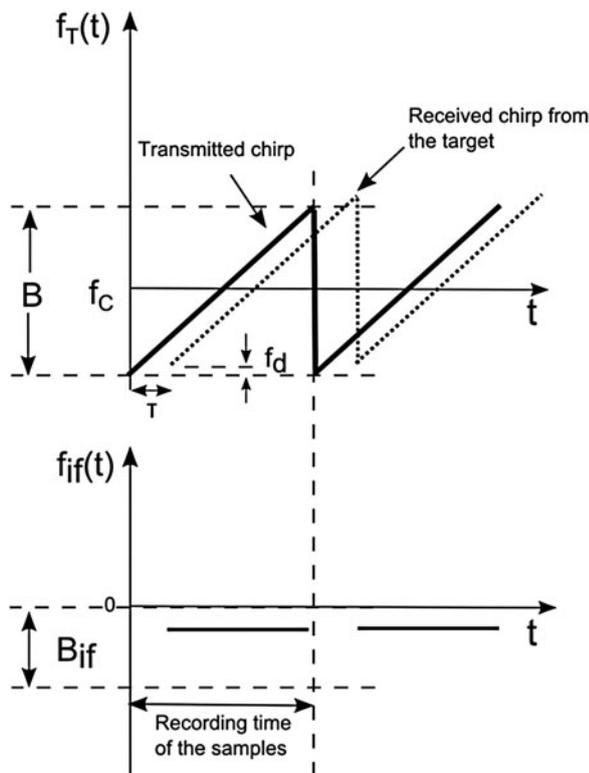


Fig. 1. AFE operation.

comparison with the desired 12 harmonic. An additional bandpass filter was placed after the frequency multiplier to filter the desired bandwidth of operation. This way the requirements for the sampling frequency could be lowered, but at the same time, some drawbacks such as harmonics generation and/or an increase in phase noise [6] might be noticed. To suppress the generated harmonics a bandpass filter was used, while the generated phase noise was partially compensated by the frequency mixer [6].

A schematic illustration of the AFE system is presented in Fig. 2, which shows a high isolation (ca. 30 dB) coupler with a coupling factor of 16 dB used in order to split the transmitted signal and to obtain the reference for mixing. The reference signal is then amplified to fulfill the minimum requirement of the mixer. By mixing the reference signal (FMCW signal) with a deflected echo signal coming from the R_x antenna, the signal at the mixer output is a sinusoidal signal with a frequency proportional to the object's range and radial velocity [5].

The beat signal generated is further amplified and filtered before sampling. The overall operation of the AFE is presented in Fig. 2. In general, combining high-pass filters with low-pass ones enables the realization of a bandpass filter, which specifies the cut-off frequencies from the desired range. Reducing the bandwidth of the received signal (which, in turn, decreases the thermal noise input in the system) is another function of the low-pass filter, in addition to selecting the differential component of the beat signal. The use of a high-pass filter, on the other hand, effectively eliminates the leakage signal [4], which is one of the main challenges in designing FMCW radars. The experiments presented in this paper were carried out with a high-pass filter installed. It is worth stressing that the frequency of leakage signals varies depending on the parameters of the transmitted chirp signal (the bandwidth and modulation period). It should be kept in mind that in the case where no high-pass filter is installed, if the leakage signal is too large it can saturate the amplifier placed behind the mixer and degrade the overall system's performance [7]. This does not occur if the paths of the leakage signal and the reference signal are of the same length, which constitutes a condition, which is hardly ever satisfied. If this is the case, the mixer works as a phase detector working only with the AC signals.

Below, in Figs 3 and 4, AFEs are presented as designed and constructed by the authors. As can be seen the AFEs are constructed from COTS components, mainly connectorized with SMA connectors. The first version of the AFE (in its early stage of development) is presented in Fig. 3. Recently, the authors have proposed an AFE system implemented on a

printed circuit board (PCB) by using surface mount device/technology (SMD). A smaller and lighter AFE with two receiving channels is presented in Fig. 4.

III. SIGNAL GENERATION AND ACQUISITION

The use of USRP devices enables easy modification of the transmitted signal parameters and the overall system configuration. The USRP is a multipurpose software-defined radio transmitter/receiver designed for low-cost experimentation and prototyping [8]. The USRP has been used only in the generation and acquisition processes, although it allows for the conducting of other operations of the signal, e.g. demodulation, filtering, etc. A functional diagram of the FMCW radar system is presented in Fig. 5. Two USRP devices and the computer are connected by a Gigabit Ethernet (GigE) interface, which enables the user to realize a maximum transfer of 50 MS/s of real-time bandwidth in both directions (transmitting and receiving) simultaneously (a full duplex). Together with the USRPs, free and open-source software can be used. Graphical programming environments such as LabView or GNU Radio allow for the construction of flow graphs, which determine the processes of the signal and the flow of data through the program.

In a FMCW radar the synchronization process is a crucial issue [9]. The easiest method of synchronizing the sample clocks of two devices is by using a multiple input, multiple output (MIMO) cable [10]. In such a configuration a single Gigabit Ethernet interface is used to control both USRPs. The USRP connected to the GigE acts as a switch, which provides data to/from both USRP devices. It also handles the time synchronization of the data so the synchronization process is transparent. The total sample rate for USRPs connected to the single GigE port on the host computer cannot exceed 25 MS/s in the 16-bit mode.

The next issue, which must be taken into consideration is the nonlinearity of the frequency sweep, which causes degradation of the resulting images [11]. The use of USRPs limits the possibility of frequency sweep correction unless one attempts to make appropriate adjustments in the FPGA motherboard of the device. The most important system parameters are gathered and presented in Table 1.

The FMCW radar with the designed AFE tested in real operations is presented in Fig. 6 below. The whole system consists of two USRPs, one for signal generation and another for signal acquisition; an industrial PC for the controlling and synchronization of the system; and the designed AFE and

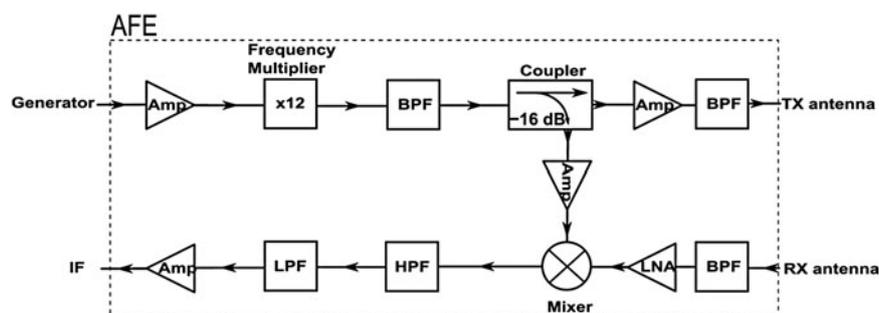


Fig. 2. AFE scheme.

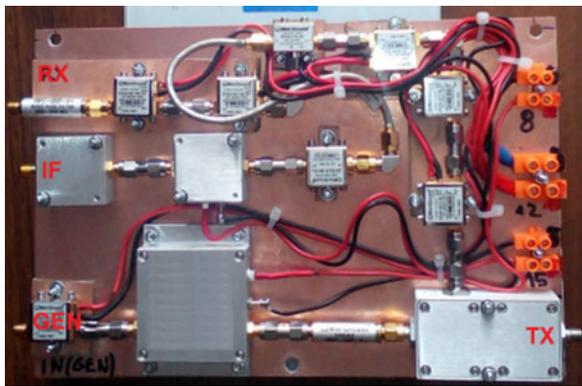


Fig. 3. AFE photo.

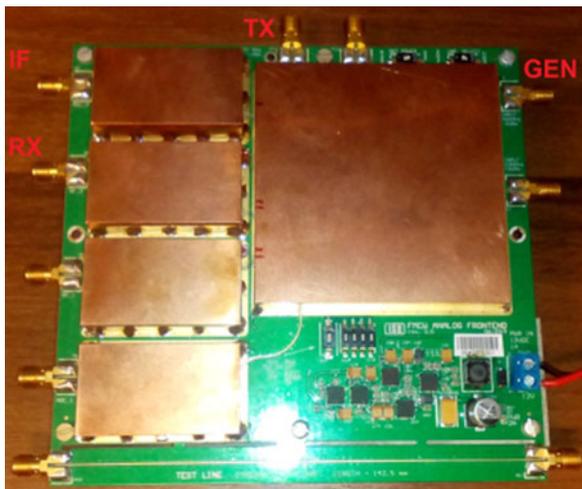


Fig. 4. AFE (SMD version).

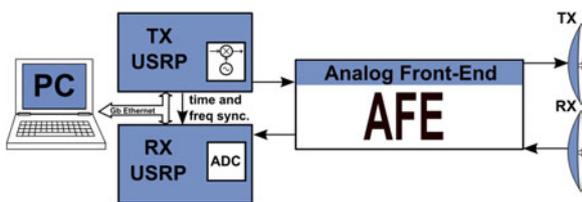


Fig. 5. Scheme of FMCW radar system with designed AFE.

Table 1. System specification.

| Parameter | Value |
|------------------------|-----------------------------|
| Bandwidth | 12–480 MHz |
| Modulation period | 0.5–2 ms |
| Carrier frequency | 5.52 GHz |
| Sampling frequency | 25 MHz |
| ADC sample bits | 16 |
| Range resolution | 30 cm |
| Cross-range resolution | 15 cm |
| System size | 20 × 15 × 5 cm ³ |
| System weight | 5.2 kg |
| Antenna size | 20 × 20 cm ² |

DC–DC converters as the power source. Four DC–DC converters were used because four different supply voltages were needed for the system, but the idea was to supply the whole system from one power source. The overall dimensions are around 20 × 20 × 30 cm³, with a total weight of 5.2 kg (including antennas and an external power amplifier) and the total power consumption is around 70 Watts. The tests of the radar system with the designed AFE are presented in the next paragraph.

IV. SYSTEM VERIFICATION

A) Laboratory test

Before the system was tested in real environments, experiments had been carried out at the Warsaw University of Technology (WUT) with the first test done in front of the WUT main building. The application of the FMCW radar for determining range and velocity information has been extensively and well described [5, 12]. The main purpose of the tests was to verify if the FMCW radar with the designed AFE would work properly and whether all requirements made during the designing stage would be met.

The test scenario consisted of a stationary radar with its antenna main lobe directed towards a moving target. With this test the authors were able to check if the radar was capable of detecting a running man (a classical FMCW moving target indication (MTI) operation) and to evaluate the effectiveness of leakage cancellation. In this case the 0 IF signal represented the echo signal reflected from the moving object (the running man) at the very close distance of around 80 m from the radar. The generated chirp signal bandwidth was 480 MHz with a chirp duration of 0.5 ms. As already mentioned, the frequency of the recorded sinusoidal signal was proportional to the distance between the radar and the running man (see equation (5)) and it changed during the 10 s of acquisition (see Fig. 8). Figure 7 presents two periods of the IF signal. The signal length is 10000 samples, which is equal to 1 ms of time (ADC sampling was 10 MHz). The maximum amplitude of the 0 IF beat signal is from −1 V to +1 V. What could also be noticed was that the chirp signals were generated with a 10% length zero gap between the chirps. The range-time matrix is presented in Fig. 8. The man moving closer to and going away from the radar is clearly visible and the cancellation of the leakage signal is also presented as there is no echo from range 0 up to 25 m.

After transforming the range-time matrix into a range-velocity matrix, the range and velocity of the running man can be determined. The results presented in Fig. 9 show the detected human body marked with a white circle. As can be seen, the man was running with a radial speed of around 3 m/s, which translates to 10 km/h at a distance of around 80 m from the radar.

In conclusion, the moving target (the running man) as well as the absence of leakage signal in the resulting image can be clearly seen, which confirms the effectiveness of the AFE system.

B) SAR test using car platform

The next set of tests of the presented AFE were carried out in Pruszkow, Poland, with the goal of verifying the possibility of

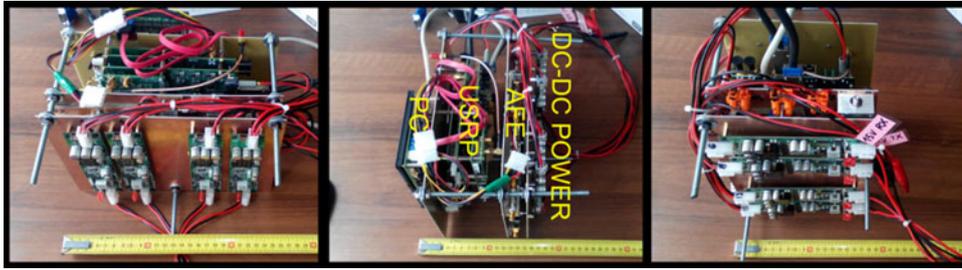


Fig. 6. FMCW radar system with designed AFE.

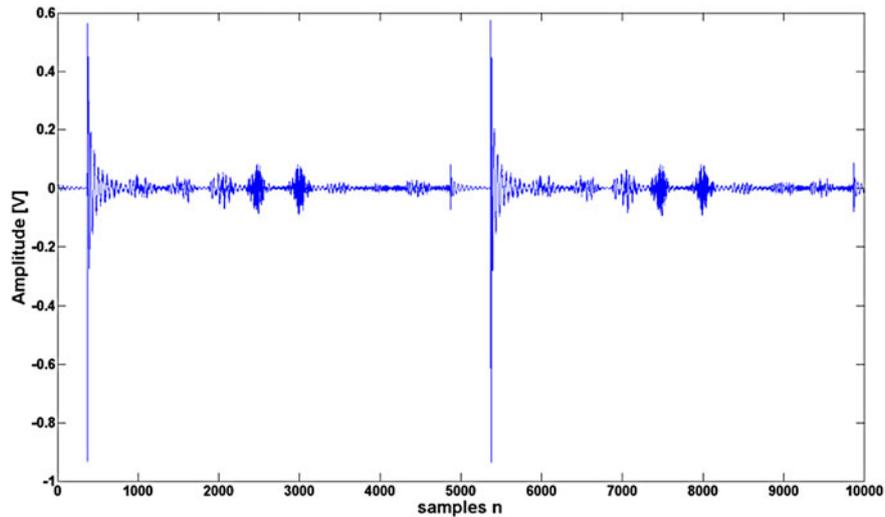


Fig. 7. The beat signal produced by two consecutive sweeps.

ground SAR imaging. The system antennas, mounted on the rooftop of the car, was set about 2 m above ground. The rest of the system – the designed AFE, USRPs and industrial PC – was mounted inside the car.

Figure 10 presents the radar system mounted in the car; the left picture shows the radar hardware inside the car, and the right picture shows the installation of the antennas on the roof of the car. For testing purposes two different types of antennas were used. Installing the antennas on the car rooftop limited the detection range, so only targets, which were visible (by the antennas) on the horizon could be imaged. In addition, reflections from near field objects limited the dynamic range of the signal. The targets of interest

were buildings and forests, which were close to the radar (up to a few hundred meters).

The scenario is presented in Fig. 11. The car was moving with a constant speed of around 50 km/h along a straight road (Przyszlosci Street in Pruszkow). The signal used to illuminate the target had a bandwidth of about 240 MHz and a pulse repetition frequency equal to 1 ms. To obtain the SAR image, an automatic signal processing algorithm developed by the authors was used. The resulting SAR image is presented below in Fig. 12 and the corresponding satellite Google Earth image of the area under observation is in Fig. 11. Due to the range resolution equal to approximately 0.6 m, determining the size of the objects was possible. The SAR image (Fig. 12) shows objects such as buildings, fences, and edges of the forest.

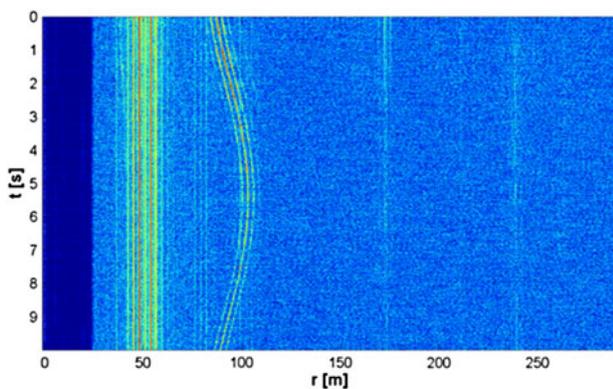


Fig. 8. The range time matrix of the first test of AFE – running man is visible.

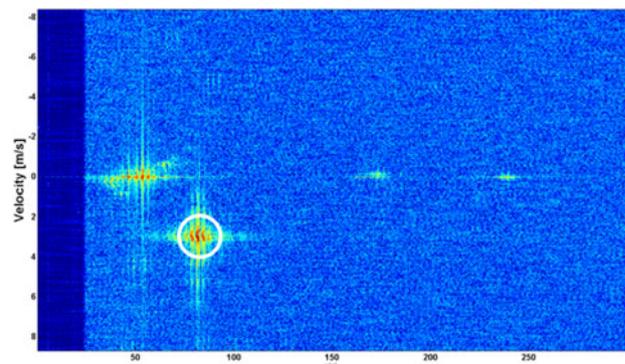


Fig. 9. The results of the AFE system in a classical FMCW performance.

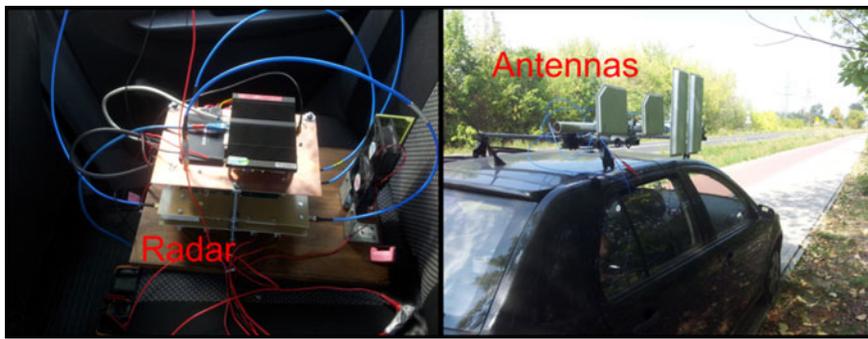


Fig. 10. Car used as a radar carrier for the first mobile tests. From the left: radar hardware (AFE, USRP and PC) inside the car. From the right: antennas mounted on the rooftop of the car.

C) Airborne SAR test

The final testing of the AFE was done in November 2013 with the goal of verifying the use of the presented AFE for an SAR

application. A small aircraft – the PZL-104 Wilga – was used (see Fig. 13) as a carrier platform for the system. The measurement campaign was carried out in the area surrounding the city of Plock in Poland.

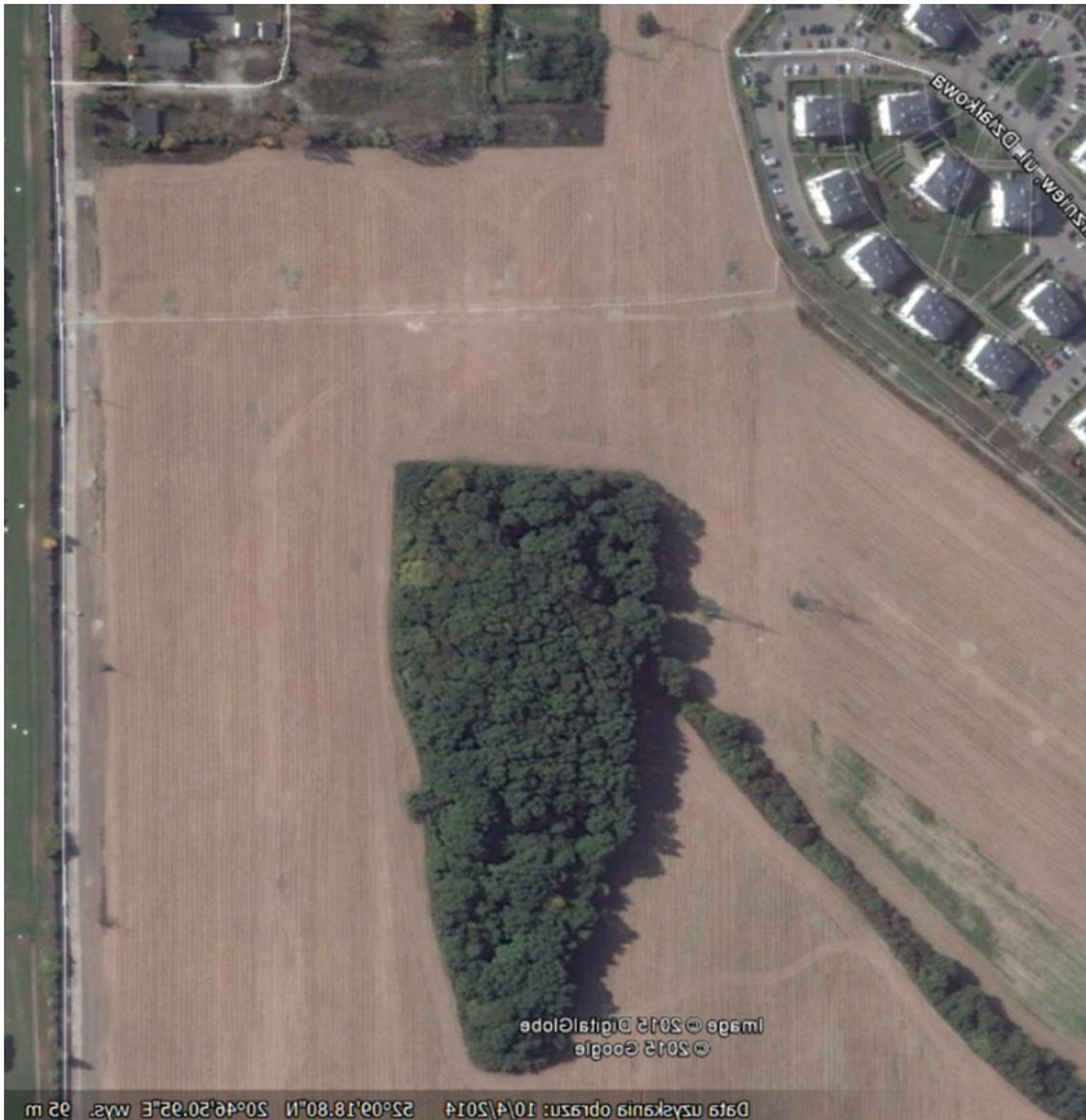


Fig. 11. Google Earth image of the scene.

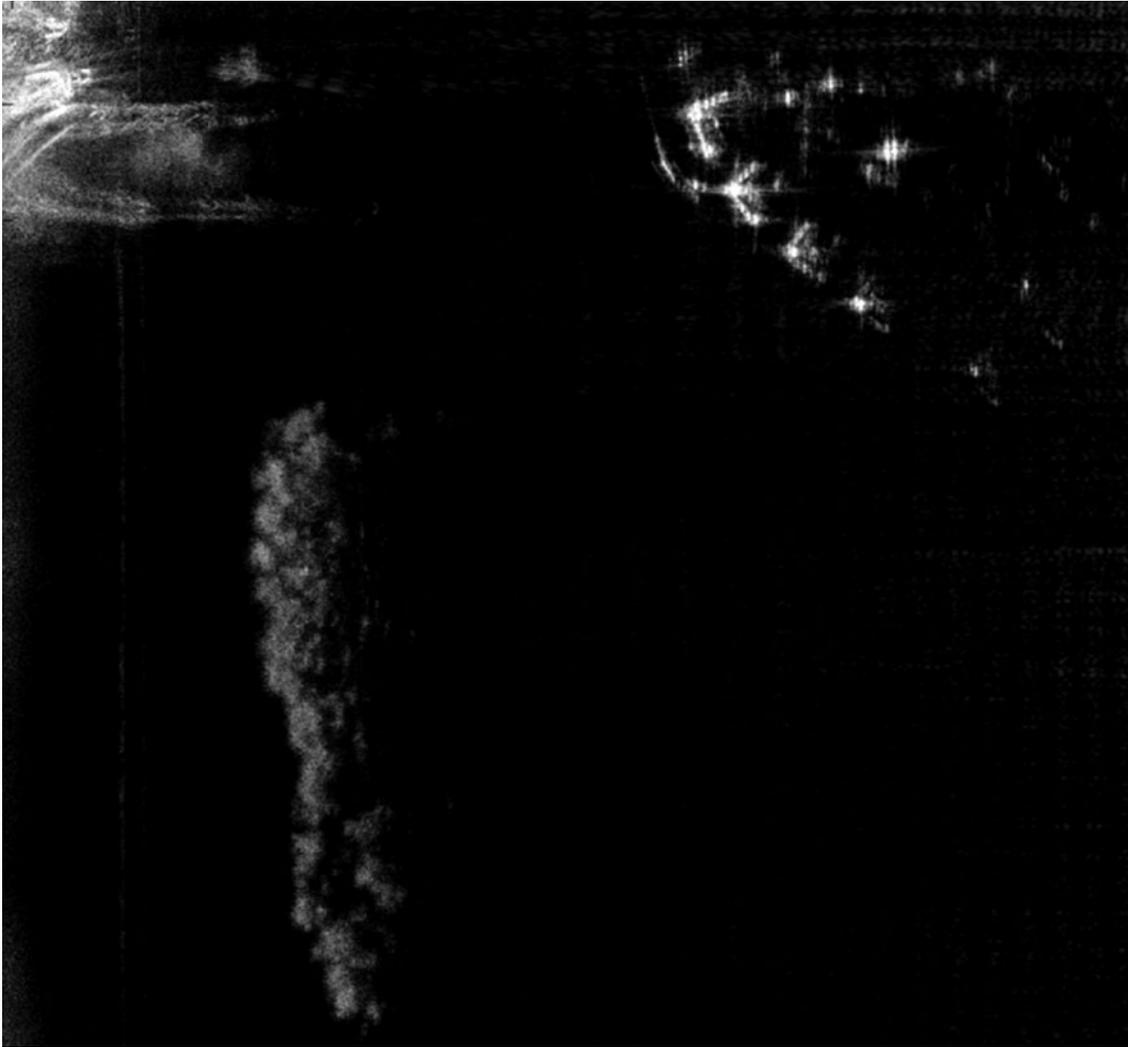


Fig. 12. Ground SAR imaging.

Figure 14 presents two consecutive beat signals. In comparison with Fig. 7 the amplitude of the signal is lower because there are no objects close to the radar. Figure 15 presents the obtained SAR image of the Podolszyce district of Plock city (global positioning system (GPS) coordinates 52.543368, 19.763692). Figure 16 shows a Google optical image of the area under observation and illuminated by the radar. Figure 17 presents a video frame from the camera

installed on board the aircraft. After comparing these images, it can be concluded that the SAR image – gathered in the microwave band – fits the objects in the optical image quite accurately. In addition comparing both images (Fig. 15 and Fig. 16) shows that, some objects have disappeared, while others have emerged. This is because the SAR imaging was done at the end of 2013, while the optical satellite image was taken at the beginning of 2010.

The result obtained successfully verifies both the effectiveness of the designed AFE and the concept of using USRP hardware for SAR radars.



Fig. 13. The radar installation on PZL-104 Wilga aircraft.

V. CONCLUSIONS

The design and validation tests of the compact C-band AFE system based on RF components were presented in this paper. The designed AFE system with the USRP devices and the PC constitute a full radar system, which can be used for research and various radar applications. The proposed AFE component of the radar system is cheap, light, and small in size. Taking into account the effectiveness and reliability of the presented system in collecting raw data, it has been

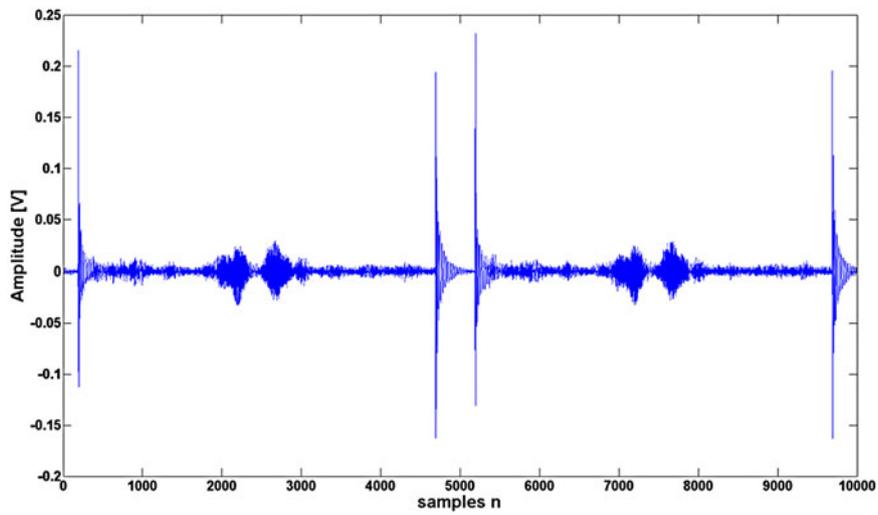


Fig. 14. The beat signal produced by two consecutive sweeps.



Fig. 15. Results of the final SAR tests: SAR image of the Podolszyce district of Plock city – (GPS coordinates 52.543368, 19.763692).



Fig. 16. Results of the final SAR tests: optical image of the Podolszyce district of Plock city, Poland – (GPS coordinates 52.543368, 19.763692). Google Maps.



Fig. 17. Results of the final SAR tests: Video frame from camera installed on board the aircraft: the Podolszyce district of Plock city, Poland – (GPS coordinates 52.543368, 19.763692). Yellow shade represents the main beam of the antenna.

decided that another AFE system based on RF components with two receiving channels should be implemented, enabling the possibility of interferometric measurements. Meanwhile, the proposed AFE system – implemented on a PCB by using surface mount technology – is currently being tested.

The SAR and MTI images presented in this paper were created with efficient, reliable, and low-cost components. Moreover, as the results show, the designed AFE can be used successfully as a radar applied for target detecting and imaging not only in academic projects, but also in real life applications.

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