

# Hardware and software front-end based on the USRP for experimental X-band Synthetic Aperture Radar

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**Abstract** This article is focused on the design of low cost electronics and software solution for the radar front-end electronics based on the Universal Software Radio Peripheral (USRP) for short range FMCW (Frequency Modulated – Continuous Wave) Synthetic Aperture Radar (SAR) system. We developed the radar front-end electronics with USRP type N210 from Ettus Research. As first, we describe requirements for SAR front-end, as second we in the detail describe the system process synchronization, the primary raw signal processing and necessary USRP FPGA program modification. Also we describe by us developed PC control program for system synchronization and raw data transfer control between SAR system high frequency part, USRP radar front-end and measurement PC. Finally, the measurement arrangement of the SAR system testing, real photo of all system and several results from the tests we show.

**Keywords** — *Synthetic Aperture Radar, FPGA radar signal processing, Universal Software Radio Peripheral, radar front-end electronics*

## I. INTRODUCTION

The Universal Software Radio Peripheral, or USRP (pronounced "usurp") is designed to allow general purpose computers to function as high bandwidth software radios. In essence, it serves as a digital baseband and IF section of a radio communication system. The basic design philosophy behind the USRP has been to do all of the waveform-specific processing, like modulation and demodulation, on the host CPU. All of the high-speed general purpose operations like digital up and down conversion, decimation and interpolation are done on the FPGA. The motivation of this work is the design of low cost radar front-end electronics based on the USRP and developing of the host control software at PC platform for light and low cost short range FMCW (Frequency Modulated – Continuous Wave) Synthetic Aperture Radar (SAR) system.

## II. GENERAL REQUIREMENTS FOR EVALUATED SAR SYSTEM

The developed SAR radar is dedicated for low altitude flying rescue plane. The general requirements for SAR system are following:

1. range resolution and cross range resolution better than 1m

2. slant range from 150m to 600m
3. swath from 50m to 100m
4. operation in X-frequency band
5. real time data processing

## III. DESCRIPTION OF THE HIGH FREQUENCY PART OF SAR

The high frequency part of this experimental SAR is described in [1]. The block diagram of SAR system including in the system used direct synthesized signal generation (DDS) is showed in Fig. 1. The DDS module is based on the AD9914 chip with internal system clock 2400MHz that is controlled by external X-tal 100MHz. The operation of proposed chirp signal generator is based on the direct synthesis via two stage frequency multiplication of DDS circuit output. It means that the digital reference chirp signal with specific sweep band is translated to higher frequencies with a larger bandwidth only via multiplications. The block diagram of such signal generator is shown in Fig.1. The reference chirp signal is created via DDS circuit (there is AD9914 in the evaluation SAR system) with internal system clock 2400MHz that is controlled by external X-tal 100MHz. The sweep band of the reference chirp signal is  $B_{ref} = 20\text{MHz}$  and its center frequency is  $f_{ref} = 450\text{MHz}$ . This highly-linear reference signal with small phase error is then filtered by a reconstruction filter (low-pass filter). Subsequently, the reference signal is multiplied by 12. It means that the new center frequency of sweep SAR signal is  $f_{c12} = 5400\text{MHz}$  and sweep band is  $B_{12} = 240\text{MHz}$ . Next, one is again filtered, in this case the band-pass filter. This operation has very important influence on spectral characteristics of the radar signal because is very important to reject all harmonics signals after multiplication. The band-pass filter was designed as the 8-sections iris waveguide filter. The filter output signal is, after some amplification, multiplied by 2 and again filtered by high-pass filter that is formed the short waveguide section. Thus generated SAR signal has finally sweep band  $B_f = 480\text{MHz}$  and center frequency  $f_f = 10800\text{MHz}$  and it meets the requirements of the proposed SAR system. The above described method of generating of SAR chirp signal requires no additional correction techniques of signal frequency nonlinearities. The quality of the SAR signal depends only on DDS circuit parameters [1].

#### IV. FUNCTIONS OF THE PARTS OF THE DEVELOPED RADAR FRONT-END ELECTRONICS

Let us introduce the set of hardware and software parameters of our radar front-end. All requirements for front-end hardware requirements have been met with use of USRP module with FPGA (see Fig.4):

1. 100 MHz digital output clock signal for synchronization with DDS module
2. 3.6 kHz digital output control sweep signal for DDS module
3. digital outputs for initialization and control of DDS module via SPI bus
4. one ADC input (minimum 12bits ADC resolution at 25MHz) for 2Vpp input voltage signal
5. the architecture with FPGA will be configured to operate with an IF (or quadrature signal pairs in the future)

Requirements for front-end software for FPGA part were satisfied by next items :

1. The possibility of decimation as the process of reducing the sampling rate of a signal in order signal to noise improvement
2. Data bypass for experimental SAR algorithm verification in to the control PC with MATLAB (at full data rate 25 M Samples per second)
3. Reliable data transfer between front-end and control PC at full data speed
4. Integration of DDS sweep signal into to the output data
5. Implementation SAR processing algorithm in the FPGA in the future
6. "Phantom" data generation for data transfer and data processing function tests purposes

Tasks of PC control software for control of the data transfer from high frequency SAR part in to the master PC via front-end electronics were:

1. Reliable data transfer and data file processing between front-end and control PC,
2. Multiple or single file data file saving configuration,
3. Binary or text file data format,
4. Software ADC input gain control,
5. DDS module configuration via SPI bus control

#### V. DESCRIPTION OF HARDWARE AND SOFTWARE RADAR FRONT-END

##### A. Hardware of USRP front-end

At the Fig.4 is showed proposed and realized hardware and software front-end. The front-end is based on the universal

software radio peripheral (USRP) N210 with XILINX Spartan 3A – DSP 3400 FPGA [2] and with input daughterboard with name "Basic RX" for input range of frequencies 1-250 MHz. The N210 comes with FPGA software under open source license. The ADC in the N210 samples input voltage signal at input "A" of "Basic RX" daughter board with 100 MHz sampling frequency and with 14 bits ADC resolution. The FPGA generates I and Q pairs for next processing as "RX DSP Chain 0" [3].

##### B. FPGA software of the USRP front-end

We modified the software for FPGA in order to processing only real data (IF) sampled by 100 MHz with 14bit ADC. So when the frontend input "A" is used, "A" is sampled in real mode as an intermediate frequency (IF) [3]. The data transfer between USRP and PC with rate 50 MB/s represents 25 M Samples per second (25MS/s). It is achieved by sending two bytes of data per sample. Each of them consists from 15 bit sampled data (after decimation by four of 100MHz cycles for 14 bit samples we obtain as result 15 bit data samples) and last bit of transferred data represent the information about sweep control signal level ("0" or "1").

##### C. Software for the measurement computer

The software for measurement PC was compiled as C++ source with Visual Studio 2010 and it uses both "Boost C++ libraries" and "UHD" library [4] and [5]. The compilation of the open source "Boost C++ libraries" has standard use according to the installation manual. The compilation of the USRP "UHD" library from Ettus Research was necessary due many crashes of compiled program at "UHD" functions original library calls. The measurement PC control program at start works with GPIO pins as the SPI initialization sequence for DDS module. In next the program starts the catching of stream of samples in the separate thread. In main thread the program processes user inputs or saves data in to the files or performing statistics measurements and functions.

#### VI. THE DESCRIPTION EVALUATION OF THE SAR SYSTEM

The performance of the designed front-end for SAR system was tested within of the evaluation SAR system (Fig.6). The SAR system was placed at the top of moving car. The data record was performing with the master PC control program with control software and GPS system. The SAR algorithm was off-line performed with MATLAB scripts from recorded data. The Fig 1.shows measured SAR map of 3 targets calculated off line by MATLAB program from real time output signal data acquired by radar front-end from HF part of SAR. In Fig.2 are shown the measured and calculated SAR map of 1 target radar corner reflector at distance 34m. The resolution is better as 1m (in both dimensions).

Next we are describing in detail measurements and several results from practical testing of the evaluation SAR system [1].

SAR system testing we have done at the parking place. HF part of SAR (Fig. 5) was placed in a passenger car, recording the output data from the radar front-end electronics was carried out by computer (laptop) with installed PC master control program for controlling digital parts of the radar.

Evaluation of the measurement was carried out off-line in the MATLAB programming environment. We were carried out following tests:

- a) Measurement with one radar corner reflector
- b) Measurement with the three radar corner reflector
- c) Measurement with the three radar corner reflector and four people

Description of the measurement procedure is here:

1. in the targets area were randomly located set of radar reflectors (1-3 pieces)
2. one moving in one direction of the vehicle was made to following the synthetic aperture track
3. recording of the data from the SAR system and navigation GPS unit
4. measuring of the actual distance between the radar corner reflectors and path of vehicle movement
5. evaluation of the recorded data (by MATLAB with SAR algorithm) and comparing the result with the actual target situation

Each recording of data from SAR system was made in the "single" mode, i.e. into one file. Radar sends continual signal with a frequency 3.6 kHz sweep to sweep the period (277.7us per period). When the sampling frequency of the digital part is 25MHz, this corresponds to about 6944 samples to each sweep time. For the actual SAR algorithm is used only part of the sample sweep up i.e. about 3472 sample. In addition, a guard interval is used at the beginning and at the end of the interval sweep up- the range is two times per 0.5us. Thus, the resulting number of samples in the distance used for SAR algorithm is 3423.

When we are considering:

1. the synthetic aperture length of about 40 meters (exact value for each assay was determined from the data of the navigation unit)
2. measurement time (i.e. time movement the vehicle car) 10s (the exact value is again determined from the GPS navigation unit)
3. and repetition period of transmitted signal 3.6kHz

then the total amount of data per measurement about 450 Megabytes.

The movement's speed of SAR system was about 4m/s. From above mentioned set of parameters the available synthetic aperture path has 36.000 measurements, which corresponds to about one measurement at 1 mm path of movement of the SAR system. From the theory of SAR it is need only one measurement at half of the wavelength transmitted signal, i.e. in this case one measuring at 1.5cm on path of SAR system. For this reason, it was included only in the MATLAB processing of each 15-th measurement, i.e. number of measurements created of synthetic aperture was

about 2400 and it led to further reduce of the volume of data processing, but had no effect on the desired resolution. In to the SAR algorithm enters the measured data matrix with size about 3423x2400. The algorithm used in the measurement had no tools for SAR system motion error compensation.

## VII. MEASUREMENT RESULTS.

According to measurements were radar corner reflectors at a distance between from 30.5m to 34 meters from the path of SAR system movement and the distance between them was 1 m or 1.8m respectively. These values correspond to reality (Fig.1). Another measuring with one internal corner reflector was the distance of about 30 meters from the path of movement of the SAR system, which corresponds to reality again. The resolution (see Fig.2) is better than 1 m (in both coordinates).

## VIII. CONCLUSION

The low cost radar front-end electronics based on the USRP and also the associated acquisition PC control software dedicated for light and low cost short range FMCW SAR system has been put into practice. Some measurements with all SAR system have been done too. Our radar front-end electronics based on the USRP acquired here raw data from high frequency part of SAR. These measurements indicate that the SAR system is functional and open for us the way for moving of the SAR algorithms from MATLAB platform to the FPGA platform which is located in the USRP. The source code for FPGA in the USRP consists from tens of modules with hundreds of lines of Verilog language. We found the places in the FPGA source code for USRP Ettus N210 where we can situate the SAR algorithms and all computing environment for our SAR system. This platform porting is our task for our next work at this field.

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Fig.1 The measured SAR map of 3 targets (radar corners reflectors)

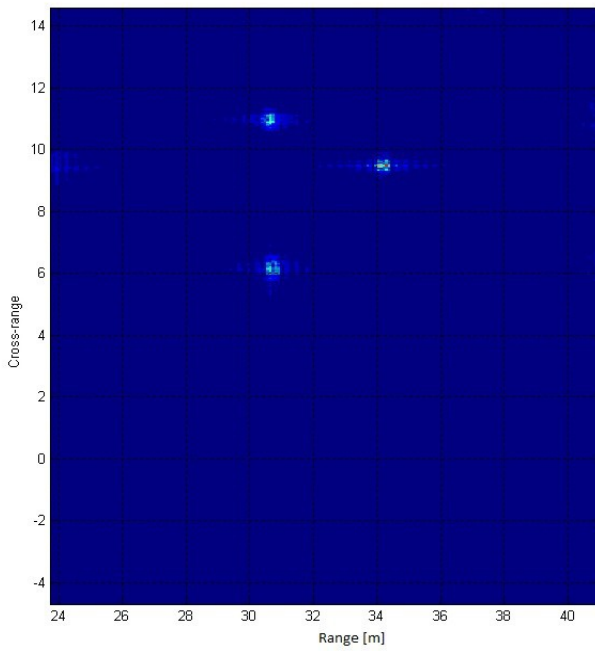


Fig. 2 The measured SAR map of 1 target in details

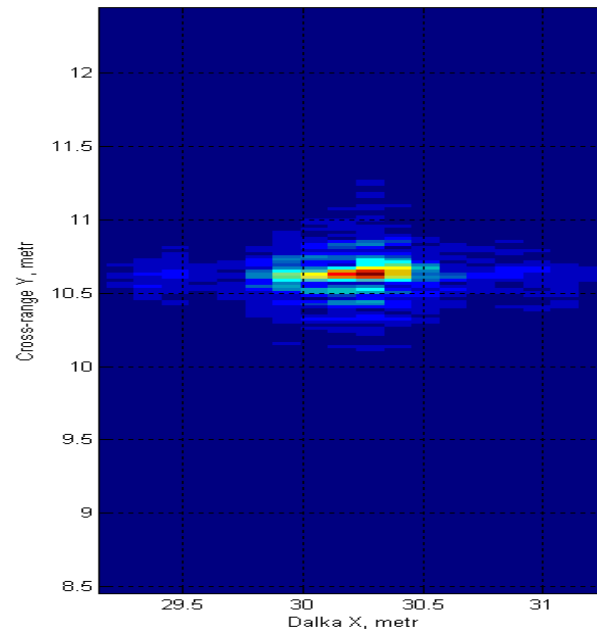


Fig.3 The block diagram of the developed SAR system

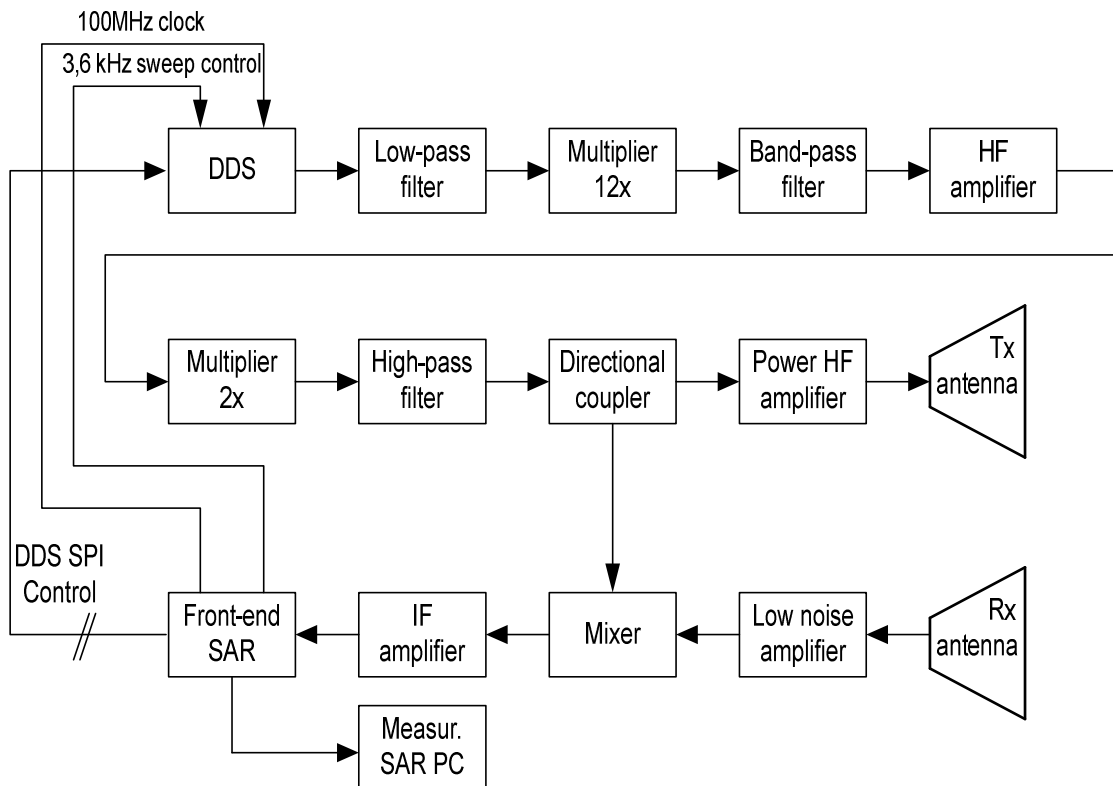


Fig. 4 The radar front-end for SAR system based on the USRP hardware and FPGA

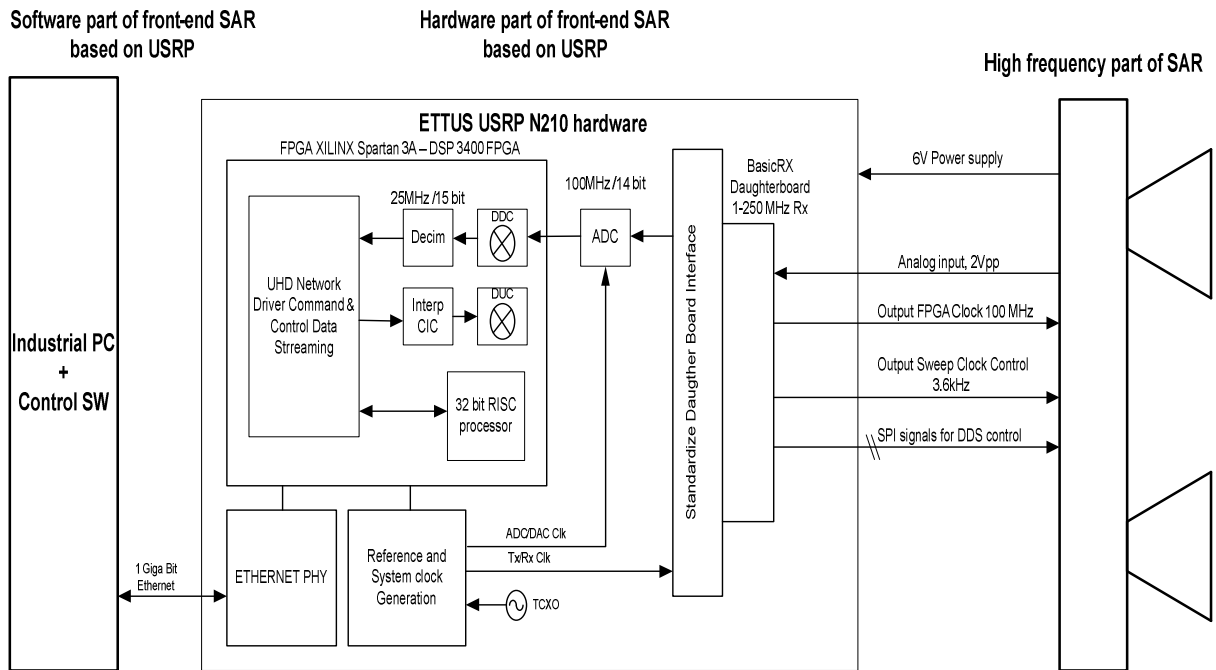


Fig. 5 The arrangement for the verification of the SAR system with front-end based on the USRP. The SAR was mounted on the moving car, output digital data from radar front-end were saved and later processed off line with MATLAB workstation

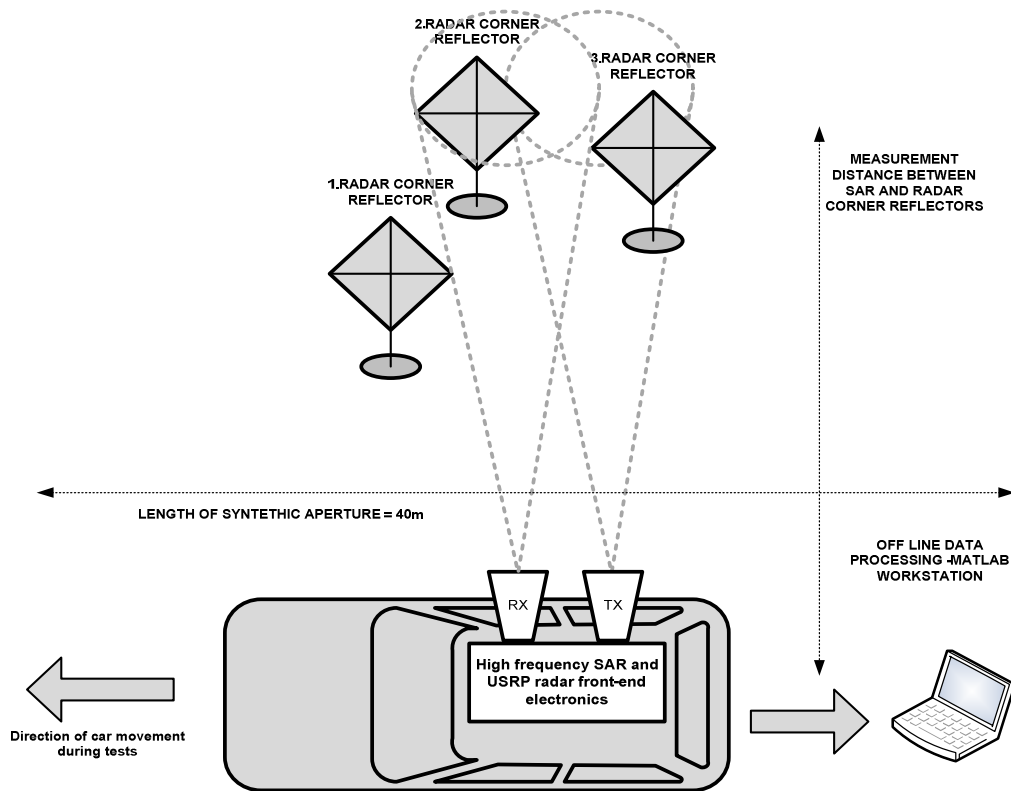


Fig.6 The phot of of the high frequency hardware of the evaluated SAR system with described radar front-end based on USRP N210 from Ettus Research

