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Experimental Proof of the Characteristics of Short-Range FM Radar Converted Signal Spectrum for a Smooth Surface

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Abstract **– This paper presents a natural experiment of the spectral processing of 4.3 GHz Frequency Modulated Continuous Wave Radar (FMCWR) converted signal. The FMCWR antennas are fixed above a smooth reflective surface. The converted signal spectrum is theoretically calculated and compared with the experimental data.**

Keywords **– Converted signal spectral processing, frequency modulated continuous wave radar (FMCWR), mirror reflection, smooth reflective surface.**

I. Introduction

The FMCWR (Frequency Modulated Continuous Wave Radar) is widely used for precise distance measurements. The simplest FMCWR does not require a linear modulation waveform. Sinusoidal or almost sinusoidal frequency modulation is easier to obtain with practical equipment [1], [2]. This principle was applied for an aircraft altimeter in the 1930s [3]. Any reasonable-shape modulation waveform can be used to measure the range, provided the average beat frequency is measured. The distance is then extracted from the beat frequency by the integral method [4]. The integral method of converted signal processing does not allow multi-target resolution [1]. The spectral methods of converted signal processing allow to extract additional information from the converted signal as well as to provide multi-target resolution. In this paper, the theoretically calculated spectrum of converted signal is compared with the signal spectrum obtained at the output of the 4.3 GHz FMCWR experimental setup. The reflection of the mirror surface is considered.

II. Theoretical Background

The propagation speed of electromagnetic waves depends on the composition of environmental air. The radial movement of FMCWR antennas or the reflective surface results in the Doppler shift of the reflected frequency. The given experiment is performed in a stable air environment; therefore the delay of the reflected signal must present a linear function of the distance. The radar antennas and reflective surface are securely fastened so that no Doppler shift is possible.

All the following mathematical expressions are made on the assumption that modulation period T_M is many times greater than time delay τ of the reflected signal. $T_M >> \tau$ criterion is true if the modulation period is at least ten times greater than the time delay of the reflected signal [5].

The instantaneous frequency of the converted signal can be expressed by formula [4]:

$$\Omega_{\text{conv}}(t,\tau)=\left|\Delta\omega\tau\frac{\mathrm{d}\gamma(t')}{\mathrm{d}t}\right|, \tag{1}$$

where

$t' = t - \tau/2$;

$\Delta\omega$ radiated frequency deviation;

τ time delay of the reflected signal;

$\gamma(t)$ modulation function.

In the case of the reflection from the mirror surface the spectrum of the converted signal will be identical with the frequency modulated signal at a frequency defined by (1). This statement is based on the assertions that the spectral width of the converted signal is much less than the frequency difference of the radiated and reflected signals, there is no Doppler shift and the delay τ of the reflected signal is constant. If the FMCWR radiated signal is modulated by the symmetrical sawtooth function, the spectrum of the converted signal can be expressed as follows [6]:

$$u_{\text{conv}} = U_{\text{conv}} \frac{\sin \pi\Delta f \tau}{\pi\Delta f \tau} \cos(\varphi_\tau - \varphi_0) +$$
$$+U_{\text{conv}} \sum_{k=1}^{\infty} \left(\frac{\sin \pi\left(\Delta f \tau + \frac{k}{2}\right)}{2\pi\left(\Delta f \tau - \frac{k}{2}\right)} + (-1)^k \frac{\sin \pi\left(\Delta f \tau - \frac{k}{2}\right)}{\pi\left(\Delta f \tau - \frac{k}{2}\right)} \right) \cos\left(k\Omega_{\text{M}} t - \varphi_\tau + \varphi_0 - \frac{k\Omega_{\text{M}}\tau}{2} \right) + \tag{2}$$
$$+U_{\text{conv}} \sum_{k=1}^{\infty} \left(\frac{\sin \pi\left(\Delta f \tau - \frac{k}{2}\right)}{2\pi\left(\Delta f \tau - \frac{k}{2}\right)} + (-1)^k \frac{\sin \pi\left(\Delta f \tau + \frac{k}{2}\right)}{\pi\left(\Delta f \tau + \frac{k}{2}\right)} \right) \cos\left(k\Omega_{\text{M}} t + \varphi_\tau - \varphi_0 - \frac{k\Omega_{\text{M}}\tau}{2} \right),$$

where

Δf radiated frequency deviation;

τ delay of the reflected signal;

φ_τ initial phase shift;

φ_0 phase shift caused by the reflecting surface;

Ω_{M} modulation frequency;

k harmonic number.

III. Description of the Experimental Setup

The FMCWR setup used in the experiments is shown in Fig. 1. The FMCWR 4.3 GHz UHF oscillator frequency is modulated by the symmetrical sawtooth voltage. Then the frequency modulated signal is radiated by the directional transmitting antenna. The reflected signal is received by the directional receiving antenna which is located 1 meter apart from the transmitting antenna. The output signal of the receiving antenna is then mixed down by the balanced mixer using UHF oscillator frequency injection. The output of the balanced mixer contains the difference of the radiated and reflected frequencies. The converted signal is then supplied to the FFT (Fast Fourier Transform) Handyscope HS3 spectrum analyser.

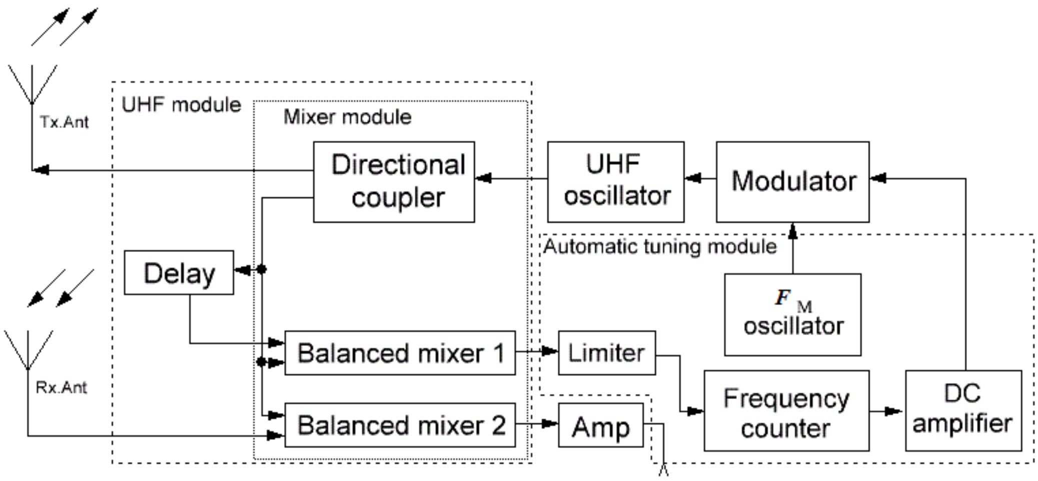

Fig. 1. Schematic of FMCWR experimental setup.

TABLE I

GENERAL CHARACTERISTICS OF THE EXPERIMENTAL SETUP

Characteristics of the Experimental Setup	**Value**
Transmitter oscillating mode	Continuous
Transmitter modulation	Frequency
Modulation voltage	Symmetrical sawtooth
Modulation frequency	150 Hz
Radiated frequency deviation	100 MHz
Radiated signal power	≥0.4 W
Transmitting antenna feeder length	3 m
Receiving antenna feeder length	2 m
Distance between antennas	1 m
Antenna beam angles in *E* and *H* planes at –3dB level	≥40°
Spectrum analyzer selected performance data	*is specified under experimental results

The receiving and transmitting antennas are located in one plane. Both antennas and the FMCWR module are securely bonded. The antenna plane and reflective surface are located in parallel and the distance between them is 3.15 m. The reflective surface is made from armoured concrete painted with alkyd type dye.

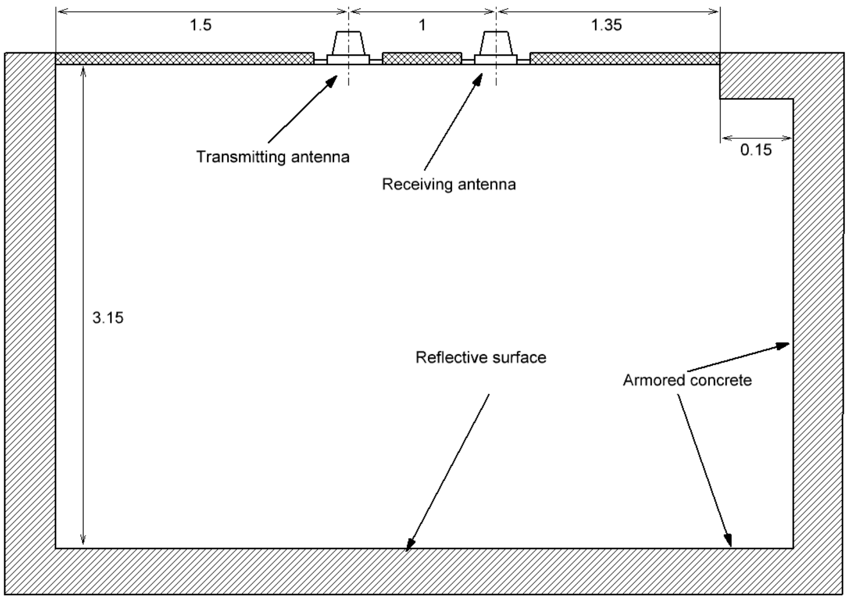

Fig. 2. Schematic of antenna layout (first side view).

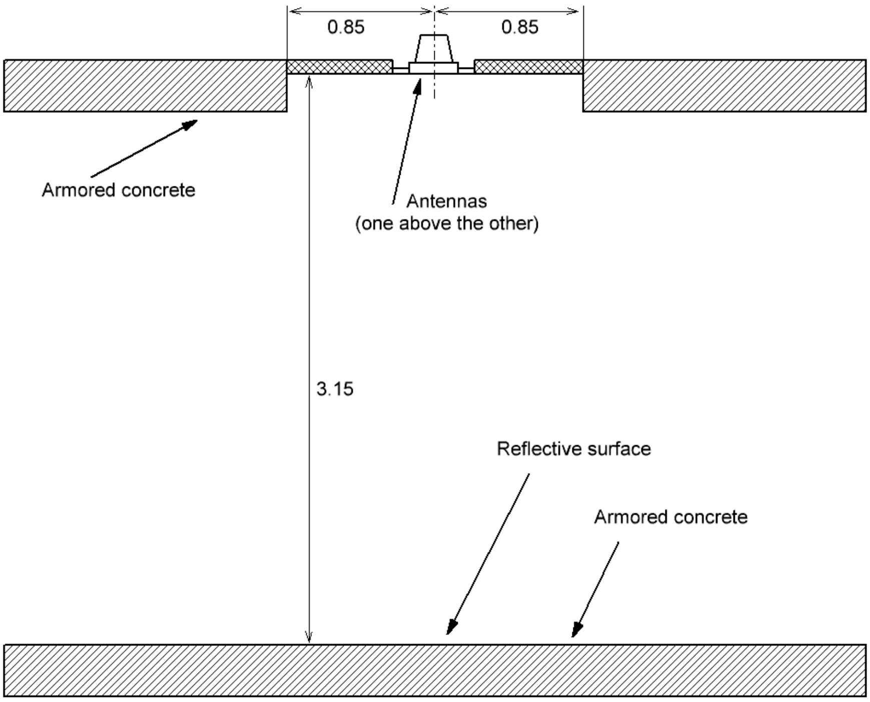

Fig. 3. Schematic of antenna layout (second side view).

The sufficient antenna beam overlap criteria are defined by (3):

$$H \geq 2D, \tag{3}$$

where

H distance between the antenna plane and reflective surface;

D distance between the receiving antenna and transmitting antenna.

As can be found by (3) and is illustrated in Fig. 4, both antennas have sufficient beam overlap.

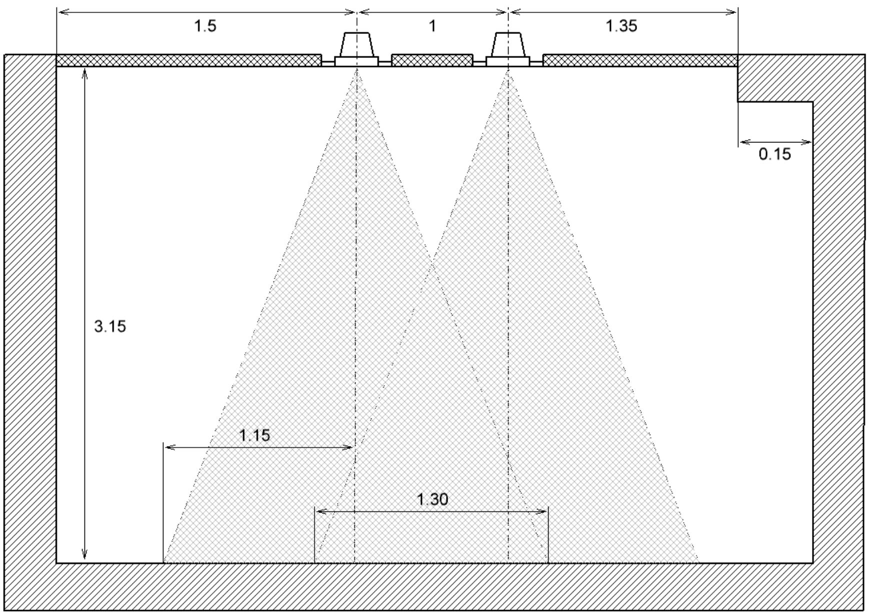

Fig. 4. Antenna beam overlap schematic.

IV. Theoretical Calculation of the Spectrum of the Converted Signal

The reflective surface can be either smooth or rough. If the mean value of surface roughness is less than $\lambda_0/16$, where λ_0 is the wavelength of the central frequency used in the experiments, the surface is smooth and a mirror-reflection occurs [6]. The wavelength of the 4.3 GHz is $\lambda_0 \approx 7$ cm, the roughness of the reflective surface is less than 0.2 cm, therefore all the following expressions are made on the assumption that the surface is smooth.

The time delay of the reflected signal can be found by formula:

$$H = 0.76(l_{\text{transmit}} + l_{\text{receive}}) + \sqrt{H_{\text{ant}}^2 + \left(\frac{D}{2}\right)^2}, \tag{4}$$

where

l_{transmit}	transmitting antenna coaxial cable length, m;
l_{receive}	receiving antenna coaxial cable length, m;
H_{ant}	distance from the antenna plane to the reflection surface, m;
D	distance between antennas, m;
0.76	coaxial cable electromagnetic wave speed (coefficient).

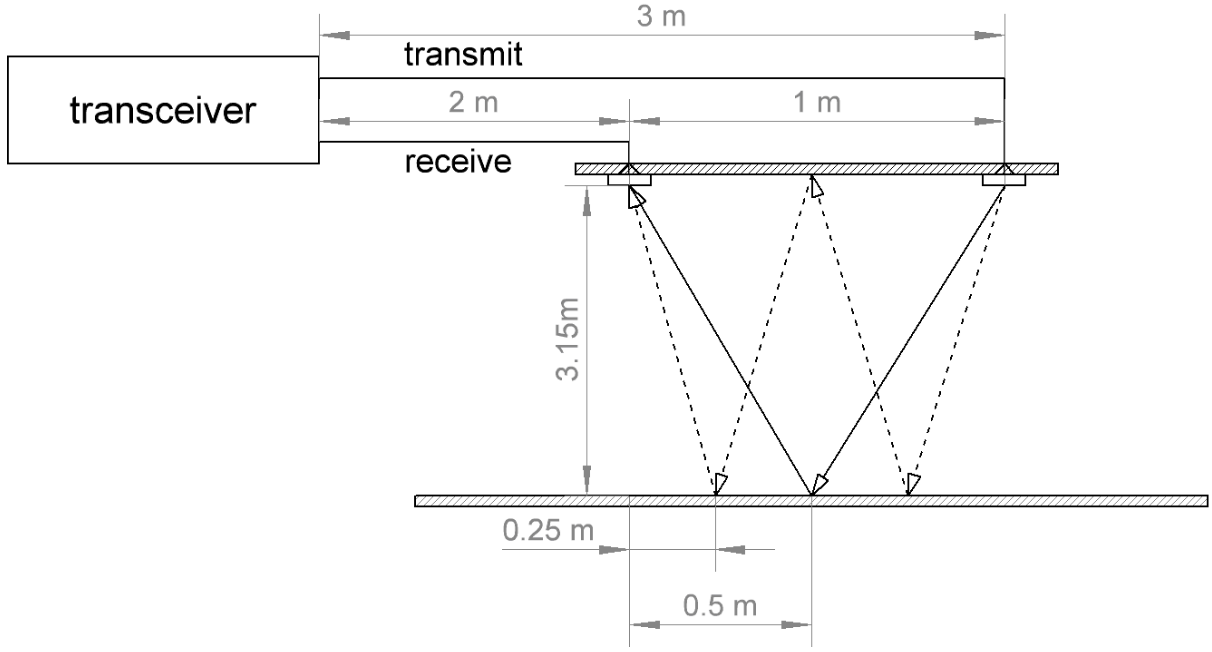

Fig. 5. Dimensions used for the calculation of the time delay of the reflected signal.

The necessary dimensions are shown in Fig. 5. By using (4), the time delay for the reflected signal is 6.989 m.

A frequency into distance transformation coefficient K_H can be found by the following expression [4]:

$$K_H = \frac{4}{C}\Delta f \cdot F_M, \quad (5)$$

where

C speed of light, m/s;

Δf frequency deviation, Hz;

F_M modulation frequency, Hz.

By using (5), the distance transformation coefficient is equal to 200 Hz/m. The central frequency of the converted signal is equal to 1397.8 Hz. The spectrum envelope can be expressed by sin(x)/x function [1]. Because of the symmetrical sawtooth modulation, the main converted signal spectrum lobe is equal to $4F_M = 4 \cdot 150 = 600$ Hz and the side lobes are $2F_M = 2 \cdot 150 = 300$ Hz wide.

Due to the absence of Doppler shift, the main converted signal spectrum lobe will contain 4 or 5 and the sidelobes will contain 2 or 3 discrete spectral components [6]. The discrete spectral components can be located only at specific frequencies defined by (6):

$$f_0 \pm k \cdot f_M, \quad (6)$$

where k = 1, 2, 3, ….

The discrete spectral components in case of f_0 = 4.3 GHz and F_M = 150 Hz were found by (6). The results for the 1397.8 Hz region are shown in Table II:

TABLE II

DISCRETE SPECTRAL COMPONENTS

k	28 666 663	28 666 662	28 666 661	28 666 660	28 666 659	28 666 658
$f_0 \pm k \cdot f_M$, Hz	550	700	850	1000	1150	1300
k	28 666 657	28 666 656	28 666 655	28 666 654	28 666 653	28 666 652
$f_0 \pm k \cdot f_M$, Hz	1450	1600	1750	1900	2050	2200

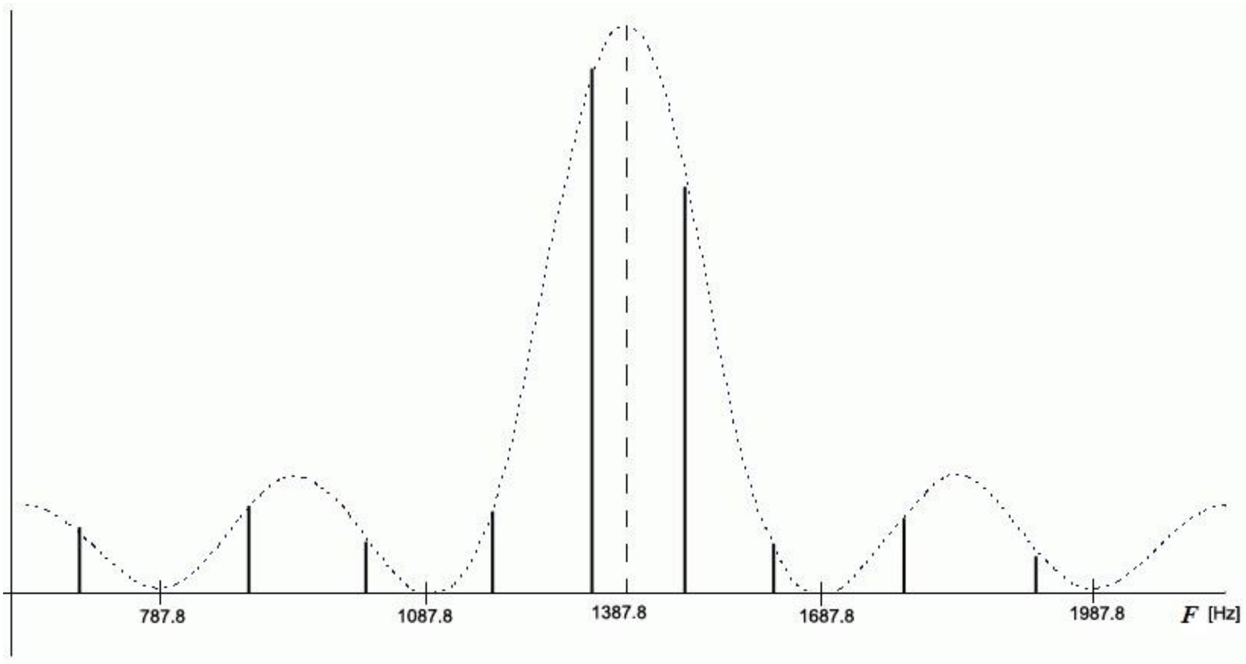

Fig. 6. Theoretical spectrum of the converted signal.

As can be seen in Fig. 6, none of the discrete spectral components matches with the maximum point of the main lobe of spectrum envelope.

V. EXPERIMENTAL RESULTS FOR THE SPECTRUM OF THE CONVERTED SIGNAL

The spectrum analyser is set to sampling frequency f_s = 50 kHz, number of samples N = 100 · 106, 12 bit resolution. Fig. 7 shows the experimental spectrum data. The main converted signal spectrum lobe is in approximately 1.5 kHz frequency.

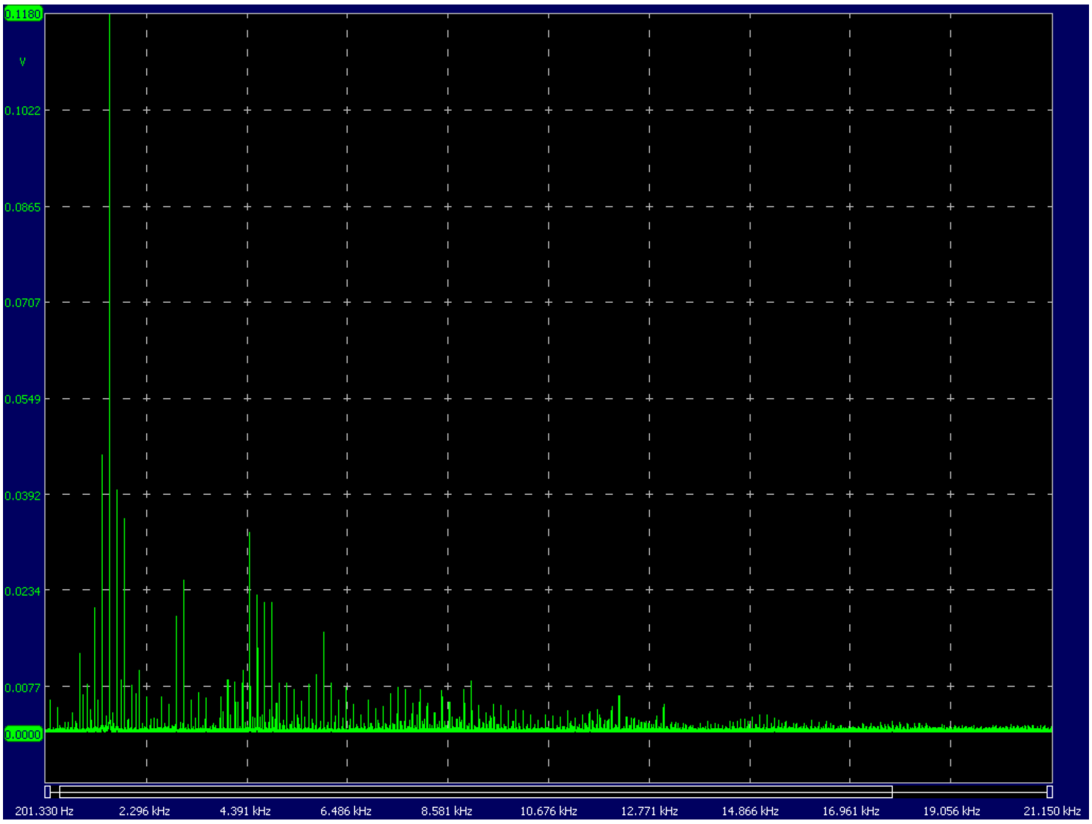

Fig. 7. Spectrum of the converted signal.

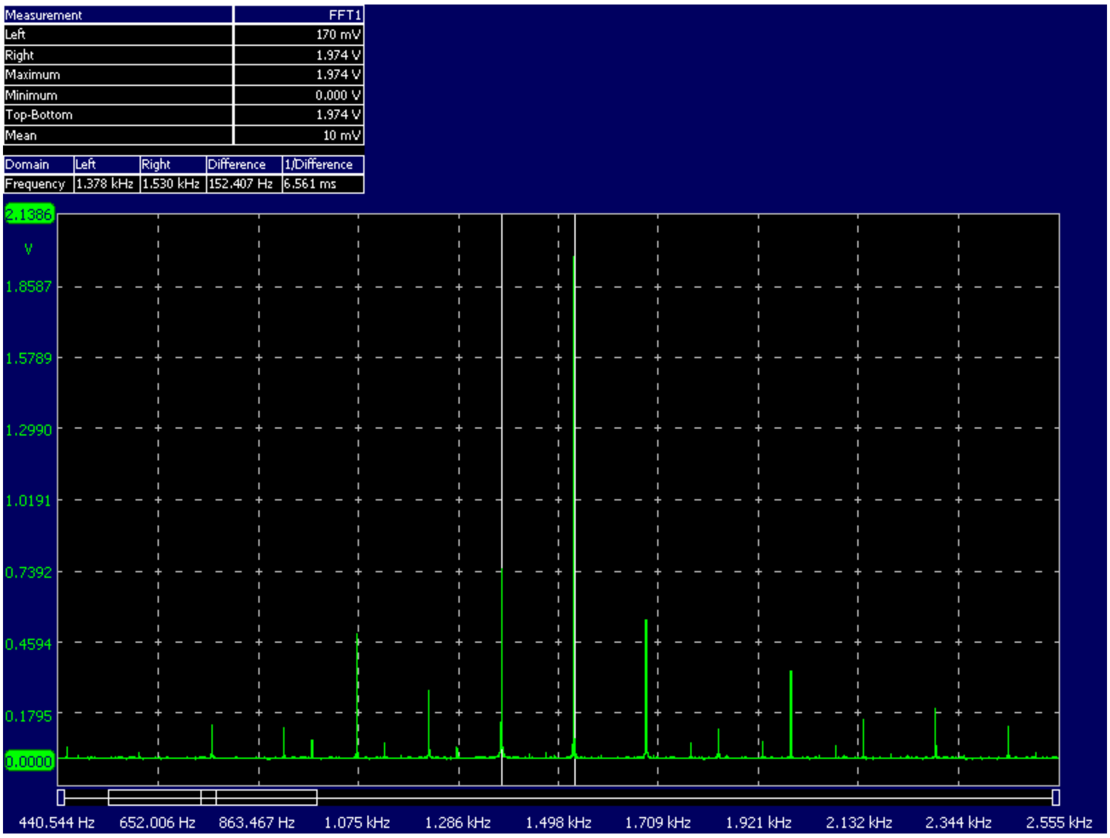

Fig. 8. Main spectrum lobe of the converted signal.

To increase the frequency resolution of FFT (Fast Fourier Transform) [6], further experimental data is obtained at f_s = 20 kHz, N = 100 · 106 spectrum analyser settings. Fig. 8 shows the main spectrum lobe of the converted signal. The maximum amplitude component frequency is 1530 Hz. It should be noted that this component is not equal to the central frequency of the converted signal (5). The central frequency of the converted signal is specified by the maximum point of the main lobe of spectrum envelope. The difference between neighbouring discrete spectral components is 152.4 Hz that is equal to the modulation frequency (2). The spectrum envelope of the main lobe is 4 · F_M = 4 · 152.4 = 609.6 Hz.

The spectrum envelope of the main and two side lobes is shown in Fig. 9. The spectrum is fully discrete as was predicted by (2). There are also additional small amplitude shifted discrete components that originate from the negative frequencies of the spectrum [5].

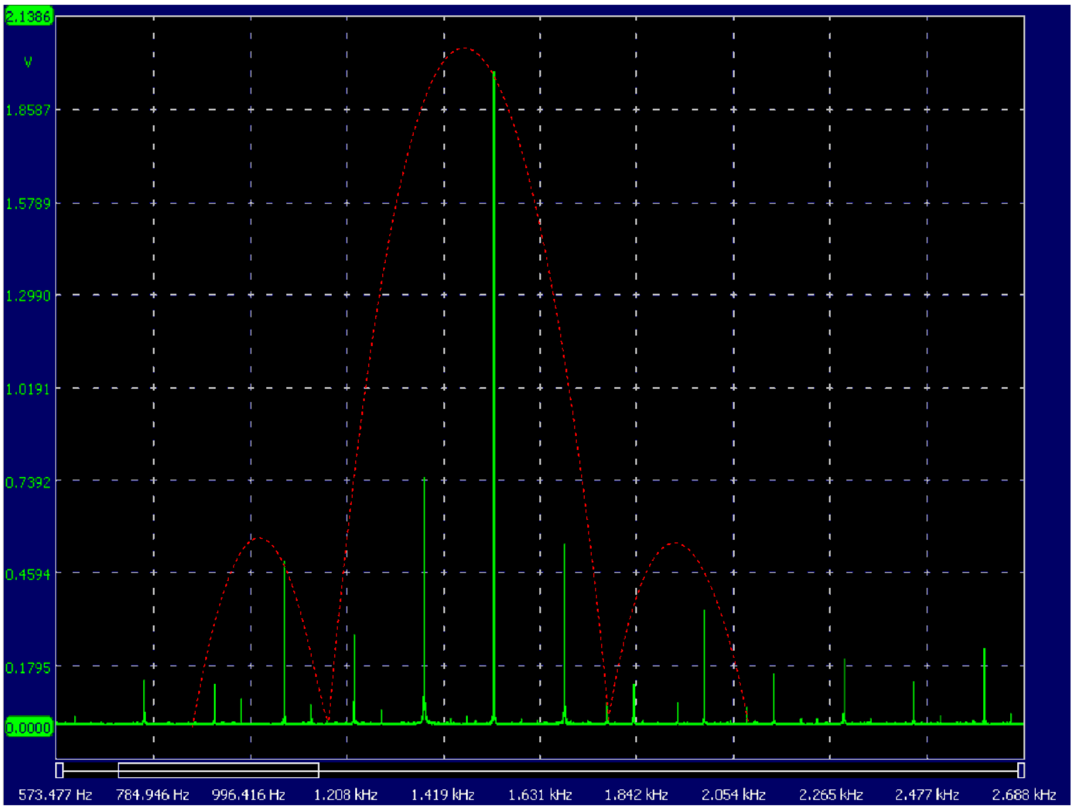

Fig. 9. Main spectrum lobe and two side lobes of the converted signal.

Slow reduction of sidelobes of the converted signal spectrum decrease range resolution of the FMCWR. The sidelobes result from phase discontinuities at the ends of modulation period [5]. If the amplitude of the converted signal drops to zero at the end of the period, the sidelobes of the converted signal will be reduced. Therefore, the converted signal amplitude modulation can be used. This method is known as weighting [7]. The weighting methods and range resolution problems are not further discussed here.

VI. Conclusion

The converted signal spectrum is discrete when the mirror-reflection occurs from the smooth surface. The difference between the neighbouring discrete spectral components is equal to modulation frequency F_M. The main lobe of spectrum envelope is $4F_M$ and both side lobes are $2F_M$ wide. At small distances, spectrum negative frequency shifted discrete components can be observed.

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