High Frequency Radar System

Carmen Monaco

University of "Roma Tre", Italy

Supervisors: Christian Frederic Adolff and Lars Bocklage

September 7, 2016

Abstract

The present work consists of the building of a small radar system that is based on the detection of Doppler shift. The basic idea is to use a low cost set up to perform field experiments and learn radar design. To save costs, empty metal coffee cans are used as antennas (called C-antennas) and all components are mounted on a plastic support. In order to evaluate the speed of moving objects, a simple program is implemented using LabView (National Instruments©) programming language. This allows the user to interact with an easy graphical interface.

Contents

Introduction

The Doppler radar is based on frequency variations of the emitted signal compared to the one received. Since the signal is reflected from a moving object the frequency is shifted due to the so-called Doppler effect. The frequency shift can be directly used to obtain speed information about objects, by analyzing how the object's motion has altered the frequency of the returned signal.
The ultra high frequency (UHF) idea, here implemented, concerns the frequency range in which the radar works. The setup is designed for radio frequencies electromagnetic waves at 2.4 GHz. The radar system concept used here is a follows. A radio-frequency (RF) signal is generated and send out to an object . The Doppler shift of a moving object shifts the frequency of the reflected signal. The Doppler shift is given by:

$$f = (1 + \frac{\Delta v}{c}) f_0 \tag{1}$$

where Δv is the velocity of the moving object, c is the speed of light, and f_0 is the resonance frequency. The change in frequency is

$$\Delta f = \frac{\Delta v}{c} f. \tag{2}$$

In the radar application the moving object affects the incoming and the reflected signal so that the Doppler shift is twice as high:

$$\Delta f = 2\frac{\Delta v}{c} f. \tag{3}$$

In the radar system, the original signal is compared to the reflected signal so that the frequency shift can be determined. Here, this comparison is done by non-linear mixing of the two signals. In this manner, the frequency difference can be directly detected. This difference frequency is in the range below 1 kHz and can be determined much easier by sampling.
The system will be used for educational purposes, like the DESY open day and pupil internship, to bring people into contact with measurement techniques with photons. The easy setup will help to understand the basic idea of radar measurements. The user can measure its on walking speed to experience changes that the radar system measures via a simple graphical interface. The system is capable to measure slow objects as a moving person but also fast velocities of cars.

1 Experimental Setup

In this section the radar setup is described.
The list of the components used is reported below, with a short explanation about their role in the experimental setup.

- The Voltage Controlled Oscillator (VCOs) provides a linear tuning with low phase noise. It is an electronic oscillator whose oscillation frequency is controlled by a voltage input. Its supply voltage (V_{cc}) is $5.0V$ and its absolute maximum tuning voltage (V_{tune}) is $7.0V$.
- An amplifier with 14 dB gain is used to bring the signal into the working range of the other devices used. It works with $5.5V$ DC voltage. The maximum output is $+17\ dBm$. One of the two amplifier is used to amplify the output of VCOs and the other one to amplify the output of the receiving C-antenna.
- The Splitter has the logical functionality to split the power of a signal input of a link between two or more output connections. It has three ports, one for the input signal and the others for the output ones.
- The Frequency Mixer creates new frequencies components from two signals applied to it. The output signal is given by non-linear mixing and, for two harmonic signals, is given by

$$cos(\omega_1 t)cos(\omega_2 t) = \frac{1}{2}(cos(\omega_1 - \omega_2)t + cos(\omega_1 + \omega_2)t) \tag{4}$$

  It hosts three ports:

  - *Local Oscillator* (LO) for the input signal that comes from the Oscillator. Its power is 13 dB;
  - *Intermediate Frequency* (IF) for the input signal that comes from the second antenna (with Doppler Shift);
  - *Radio Frequency* (RF) for the output signal (convolution product).

  Figure 1 shows a schematic representation of the Frequency Mixer.

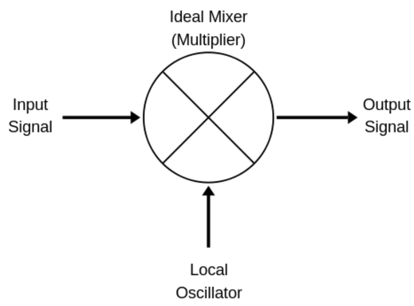


Figure 1: Frequency mixer symbol.

- The C-antennas (coffee metals) act as open-ended circular waveguide antennas. The cans have a diameter of approximately 10 cm. The dominant $TE11$ circular waveguide mode is dominant. The cutoff wavelength is approximately 17 cm corresponding to a cutoff frequency of 1.8 GHz, which allows good performances for an operation frequency of ~ 2.4 GHz.

- The NI myDAQ (white box) is a low-cost portable data acquisition *(DAQ)* device that uses NI LabVIEW-based software instruments. It was used as voltage source of V_{cc} and V_{tune} but also as an audio-wave receiver for the mixer output. Its Maximum Sampling Rate is 200 KS/s.

In Figures 2 and 3 the assembled setup with all components and a corresponding scheme are shown:

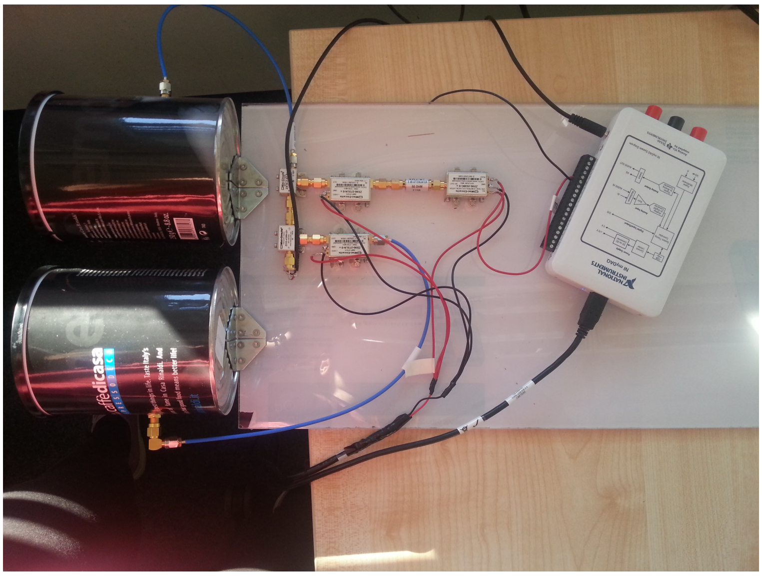


Figure 2: Photograph of the assembled radar setup.

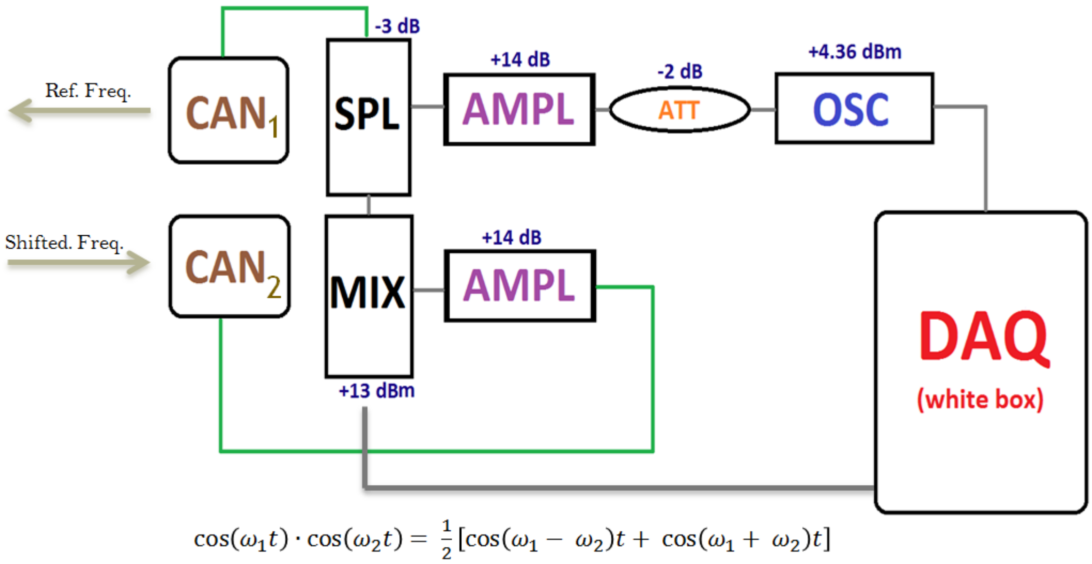


Figure 3: Scheme of assembled radar setup.

It is useful to describe the behavior of linear electrical networks when stimulated by electrical signals with so-called $S - parameter$ of the *S-Matrix*. S is the scattering matrix, that relates the initial state and the final state of a physical system undergoing a scattering process. For the 2-port network the matrix elements can be summarized as follows and represented as figure 4:

- S_{11} is the input port reflection coefficient;
- S_{12} is the transmission coefficient from port 2 to 1;
- S_{21} is the transmission coefficient from port 1 to 2;
- S_{22} is the output port reflection coefficient.

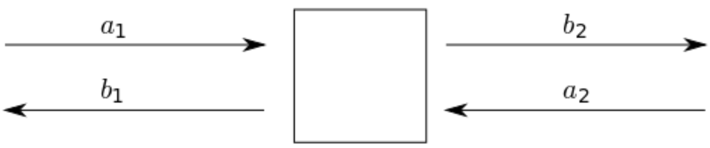


Figure 4: Two-Port S-Parameters.

A particular physical relation exists between the $S-parameters$ and the input, reflection and transmission power (a and b in figure 4). In the radar case, the only interesting parameter is S_{11} and it is used for the C-antennas testing. In order to assemble together all radar components in a correct way, without any damage, it was necessary to add a 2 dB attenuator in the setup that reduces the amplitude of signal.

1.1 Characterization

At first, all the components are tested to verify that they worked properly.

Voltage Controlled Oscillator (VCOs)

The VCOs device was connected to the voltage source V_{cc} of 5.0 V and V_{tune} 1.5 V to measure its resonance frequency with a spectrometer analyzer. This instrument measures the spectrum that shows the intensity as function of frequency. Figures 5, 6 and 7 show how changing the tuning voltage modulates the frequency. or the actual setup, V_{tune} was set to 1.5 V, so that the radar system operates at a frequency of 2.37 GHz.

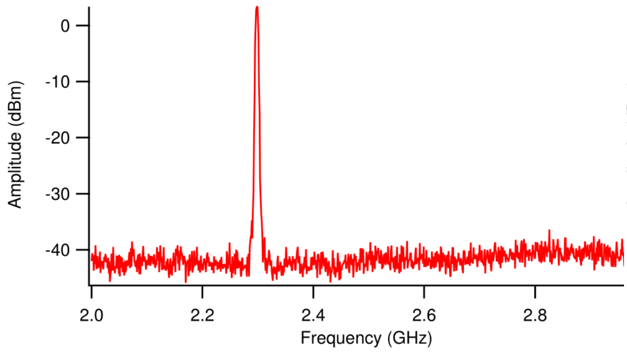


Figure 5: Graph with V$tune$= 0.5 V and f_{osc} = 2.29 GHz.

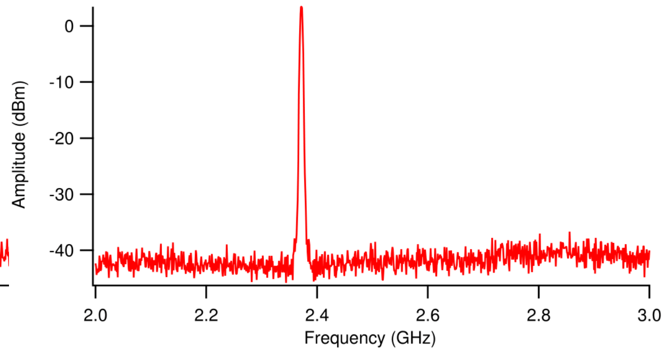


Figure 6: Graph with V$tune$= 1.5 V and f_{osc} = 2.37 GHz.

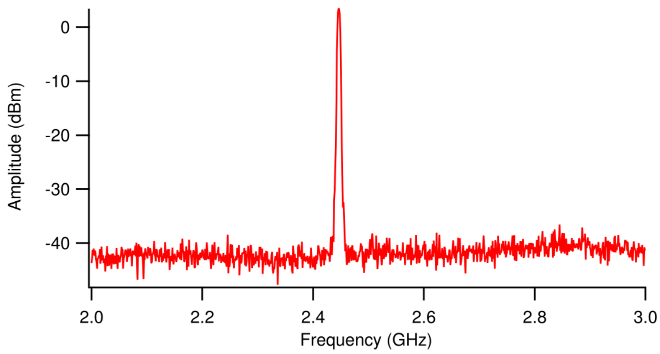


Figure 7: Graph with V$tune$=2.5 V and f_{osc} = 2.44 GHz .

In figures 5, 6 and 7 is possible to notice the peak shifts with the different applied voltage V_{tune} and the low signal with noise ratio of 40 dB.

Splitter

The Splitter was tested with the same spectrometer analyzer and it was possible to check whether it worked properly in a symmetric way in the range of interest. Half of the power of the input signal went to the port one and the other half to the port two.

Frequency Mixer

The Frequency Mixer was tested with same instrument, setting V_{cc} at 5 V and V_{tune} at 1.5 V and without any moving object in the range of the C-antennas. The VCO was connected to the amplifier. Afterwards, a splitter was used to feed the LO input and the input signal of the mixer. The device demonstrated to work properly and from figure 8 it's evident that the left peak at 0 Hz corresponds to the difference of the two signal frequency and the right one at double the operating frequency, i.e. the sum of the frequency of the two input signals. This is exactly the expected result from the non-linear product. The middle peak is due to the imperfect isolation of this device: in fact the data sheet isolation value is 14.4 dB and the gain of amplifier linked to it makes sure that its amplitude is quite zero as shown.

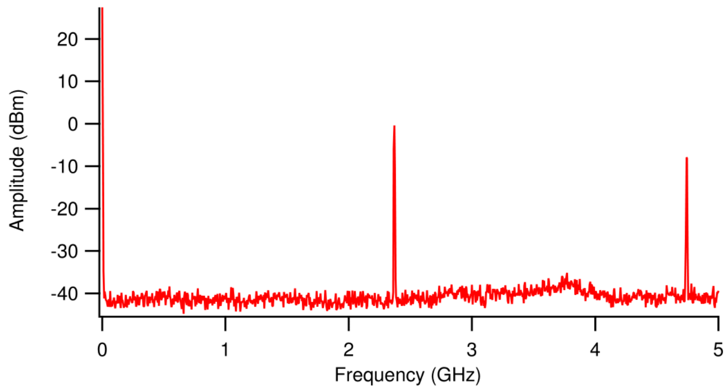


Figure 8: Mixer testing.

Cantennas

At 2.4 GHz the free space wavelength is 12.5 cm and to excite the TE11 mode a one-quarter wavelength-monopole thin-wire probe with length 3.1254 cm (as measured from the tip of the probe to the base of the coffee can) was used. The basic idea is that C-antennas had to match with the other radar components and every device has a 50 Ω wave impedance. A vector network analyzer was used to characterize the C-antennas. This instrument measures the S-network parameters of electrical networks.

In order to compare the well matched antenna (3.25 cm length) with the that has not been matched to 50 Ω wave impedance (6.2 cm length), the measurements were made before and after the cut of the wire probe.
The results are shown in figures 9 and 10. The low reflection at 2.4 GHz is visible after the impedance matching with value of -30 dB. So, almost all power is transmitted by the antennas at the operating frequency.

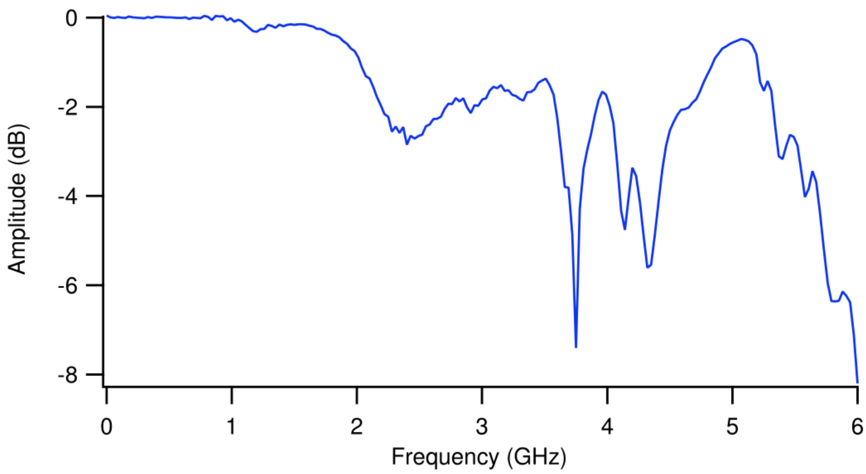


Figure 9: C-antenna without matching.

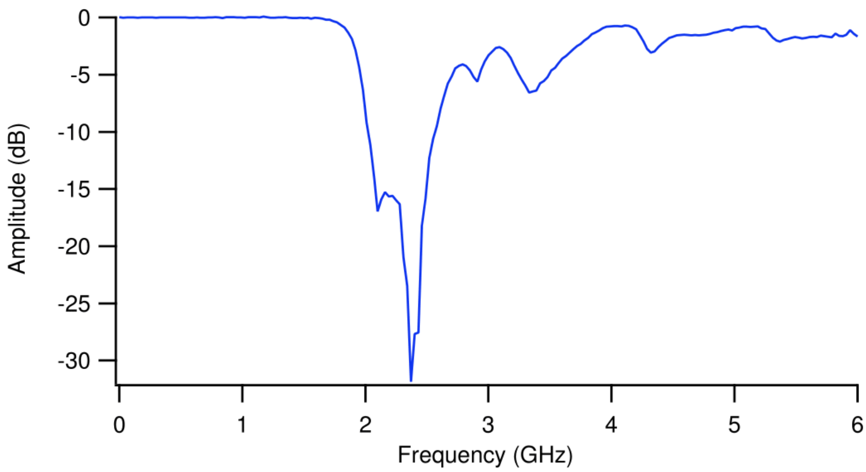


Figure 10: C-antenna with matching.

2 Data Acquisition

2.1 Signal Theory

The basic idea that has been used in this work is linked to the *Nyquist Sampling Theorem*. It provides a prescription for the nominal sampling interval required to avoid aliasing. It may be stated simply as follows: the sampling frequency should be at least twice the highest frequency contained in the signal. In mathematical terms:

$$f_s \geq 2f_c \tag{5}$$

where f_s is the sampling frequency (samples are often taken per unit of time), and f_c is the highest frequency contained in the signal. In this context, to detect the frequency required for the calculation of velocity, the *FFT (Fast Fourier Transform)* was applied to the output signal coming from the Mixer. The FFT generates the same results of DFT (Discrete Fourier Transform) but it's faster. In fact, in the graph representing the Fast Fourier Transform the x-axes ranges is $(-f_s/2\ ,\ f_s/2)$.
Once the setup was complete, a specific LabView Program was made, which includes the calculation of the moving object velocity and shows its Color Plot. LabView is a graphical programming language developed by National Instruments©. The user interface and the results are discussed in the next section.

2.2 Results

This section presents the results obtained using a moving car. Data were taken at different speeds in order to test the correct working of the radar. The specific values of sampling rate, the number of measurements and the lines in the graph were chosen in order to reach a good compromise between the maximum detectable speed, the device resolution and measurement time. In particular, figure 11 shows the simple graphic user LabView interface, here displaying that the measurements were made with the specific values mentioned before. Figure 12 shows the Radar-code, to get an idea of the LabView programming. The programm plots the raw sampling data. the FFT, and the measured velocity that is determined by a peak detection in the FFT.

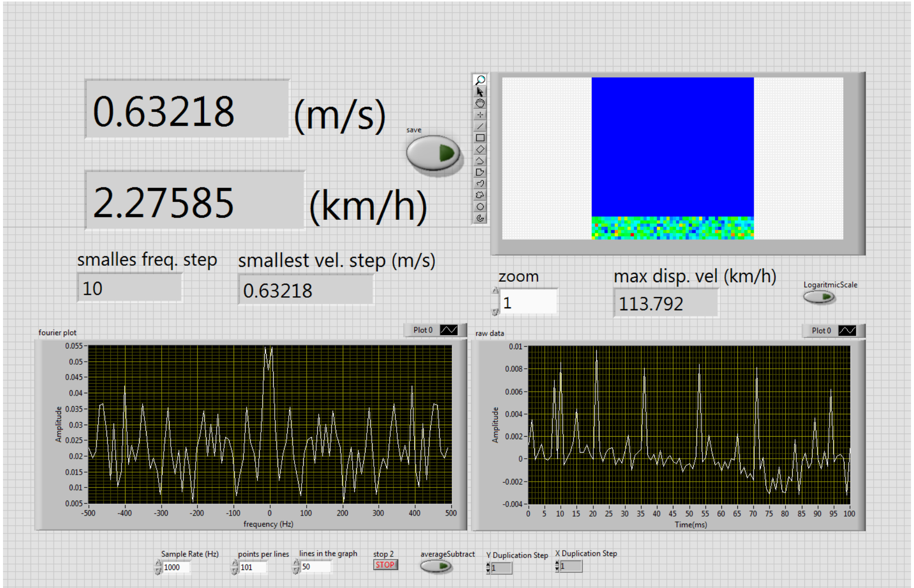


Figure 11: LabView-User Interface.

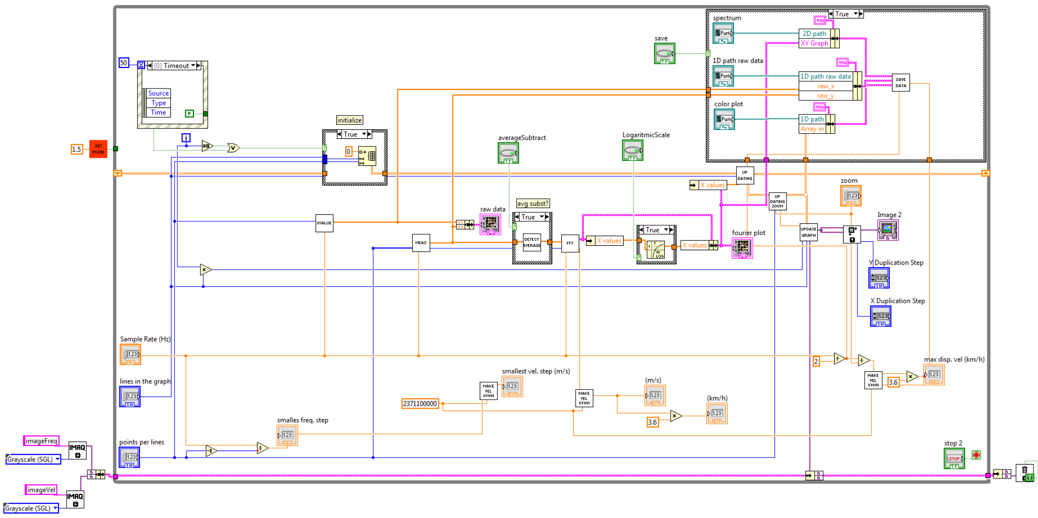


Figure 12: LabViev Radar-Code.

The following speed values with the aid of a moving car going at the specific velocity as indicated by the speedometer of the car were tested: 20 km/h, 25 km/h, 30 km/h and 40 km/h. The Color Plots, that the program produces for each speed, were analyzed with IgorPro software. This graph describes the temporal evolution of the data and each line represents a measured spectrum. The each Fourier wave line profiles allowed to evaluate the speed. Figures 13 and 14 are an example of these measurements in the specific case of $v = 40$ km/h and with specific parameters.

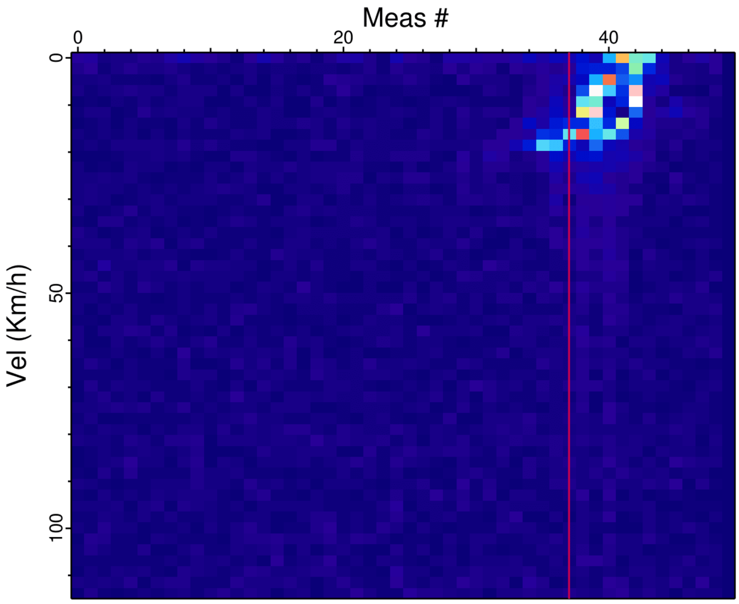
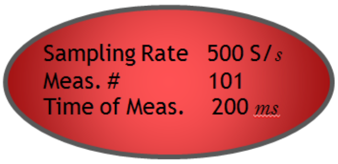


Figure 13: Color plot of the velocity components for subseqent measurements. The car was moving at 40 km/h.



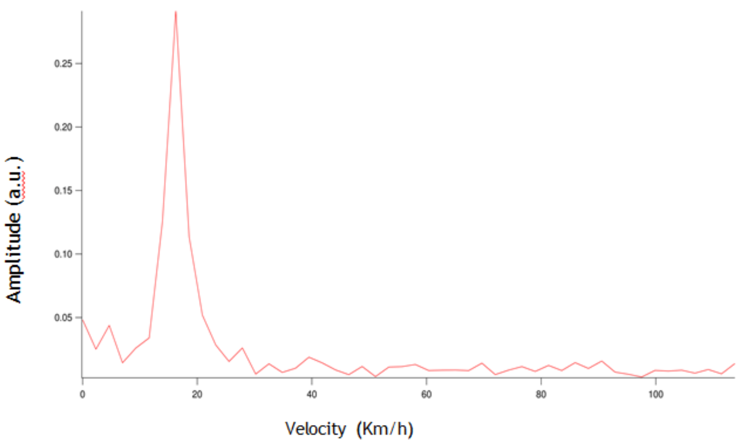


Figure 14: Line Profile for velocity 40 km/h from the red line in graph 13.

Possible parasitic peaks at zero frequency can be suppressed by subtracting the average of the time signal, as can be see in figure 14. Note that also the distance of the object to the radar is important. Good measurement for a distance below 3 m can be achieved. As can be seen in figure 14, there is a maximum in the Fourier spectrum that detects the car speed according to the Doppler shift equation.

Finally, to check the expected linear trend of the measured velocity, the speedometer values were compared to the measured values from the radar system. A linear fit was made, reported in figure 15. The red crosses represent the speed measurements and the blue line is the linear fit. On top left, fit parameters are also reported.

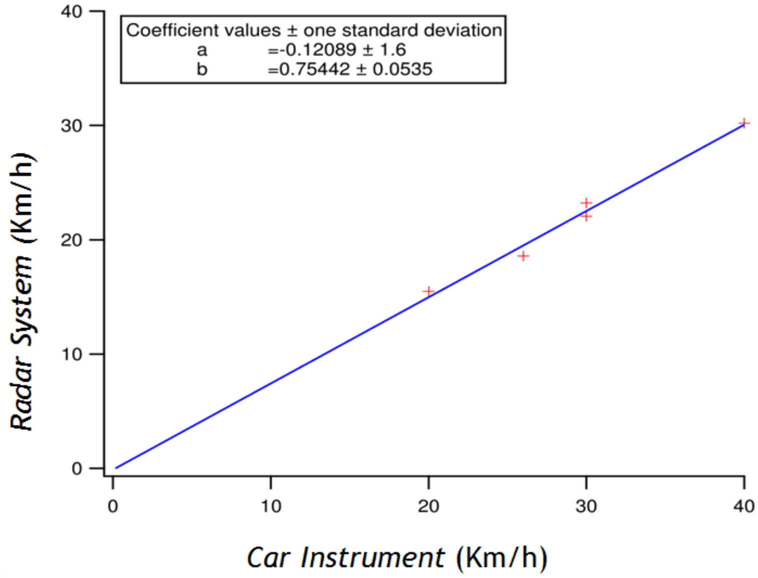


Figure 15: Data fit.

The final results show a properly operation of the radar. As expected, the intercept value of the fit is close to the origin and the slope differs from the expected value 1 by ∼25%.

Conclusions

A radar system was built wit low cost materials, with quite satisfactory results. The coffee-cans demonstrated to work properly as antennas. In addiction, a 25% deviation was found in the radar testing phase and could have different reasons: imperfect detection of peaks in the Fourier spectrum or the experimental data acquisition, or even the particular slant of the radar with respect to the moving direction of the car. This would mean that not the entire speed was evaluated, but only the component that is directed to the C-antenna.
The maximum detectable velocity depends on the the sampling rate: in the example explained before, in principle, is more than 100 Km/h.
In conclusion, it has been shown that the radars system delivers robust measurements of the Doppler shift that is proportional to the velocity of a moving object.
Next steps to improve the radar system could be the code implementation of zero padding for the FFT spectrum and the FMCW (Frequency-modulated continuous-wave). The latter allows to have time information about the signal and then the distance of moving object.

References

[1] Lincolcoln Laboratory, Massachussets Institute of Technology *Gregory L.Charvat, Alan J.Fenn and BradleyT.Perry*