

Report on workshop with FMCW radar

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1 Introduction

In this report we discuss a workshop that was conducted in the course ”Introduction to Scientific Research”. As part of the effort to document the experiment to make it reproducible, we describe the parameters of the experiment, data processing steps and physical principles that explain the experiment. We also discuss objectives and general structure of the workshop.

The workshop is centered about a radar experiment and analysis of the radar output data with the objective to recognize an object opposite of a radar.

The workshop can be divided it into two parts: the first is the radar setup, launch of measurements and data retrieval, and the second is the data processing. In the measurement part, we installed the radar in a relatively open area, with no visible obstacle on the line of sight between the radar and the object. After making a series of pulses and collecting the received reflected waves, we place a solid object in front of the radar. We note the distance between the radar and the object, and repeat the measurements.

The role of data processing is then to compute distance information about the surrounding objects from both of the measurements. By calculating difference between the two, we can obtain information on the environment change, or in other words, we can clearly identify a new body and distance to it. This body should be found exactly where we placed the object before the second round of measurements.

The objective¹ of the workshop is to show the complexity of modern scientific work. In the span of 3 hours we covered experiment materials installation and the importance of a proper method that minimizes errors, discussed the main principle of the radar and the logic of its output processing in order to calculate the distance data. This covers at least the general ideas on experiment organization, some elements of physics and math, and computer tools on numerical calculations.

The report is divided into several sections. Section 2 presents the experiment setting, including physical placement of the hardware, parameters and type of the radar, as well as its general structure. Section 3 explains the working

¹The objectives are inferred and may be incorrect.

principle of the radar. Section 4 describes the complete procedure to obtain distance to an object. Section 5 discusses ways to improve the experiment by describing factors that could lead to errors. Section 6 concludes the report.

2 Radar setting

2.1 Placement

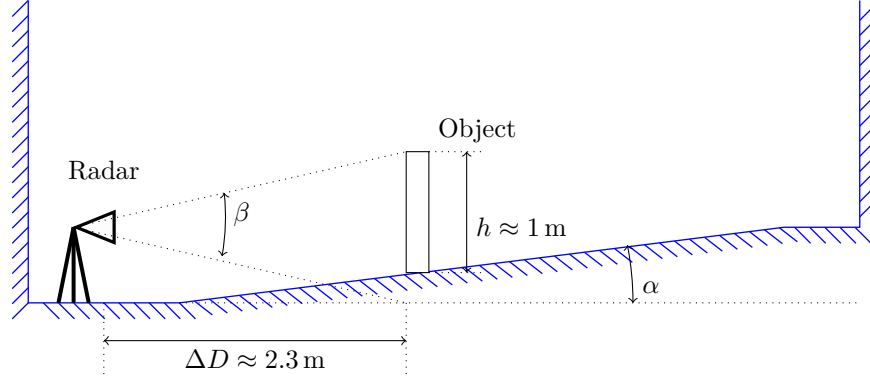


Figure 1: Physical setting of the radar and objects

In Figure 1 we describe the radar placement in the space. The radar is placed opposite to a building, on a flat surface that goes into a slope of angle α , which leads into another building. On the slope we place a target object of height h . This object is a part of the second round of measurements.

2.2 Internals

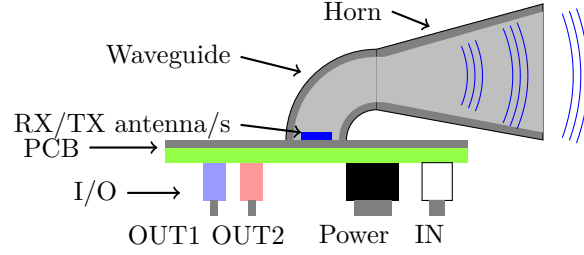


Figure 2: Radar schematics

Figure 2 presents the approximate schematics of the radar: connections, circuit and antenna feed. The printed circuit board (PCB) contains several elements, such as:

- a power connection for signal amplification;
- input/output (I/O) connections, one for the signal to be emitted and 2 receiving channels, from which only the second one is used in the experiment;
- antennas to receive and transmit electromagnetic radiation.

The construction above the antenna is called an antenna feed. It is used to make the design more compact, while achieving directional high density radiation. The waveguide collects more or less unidirectional wave of the emitting element and forces it into a particular direction, in this case to the horn.

The idea of the horn is that it slowly "adapts" the wave to the space after the opening. Otherwise a reflection can happen due to a big difference in impedance on the edge between waveguide and open air (or open space). Thus this preserves radiation density that was achieved with the initial usage of a waveguide.

Exact circuit schemes or their components, or the name of the radar series are unknown.

2.3 Characteristics

Important experiment parameters, including radar characteristics (? means unknown):

- radar chirp (Fig. 5):
 - frequency function form: sawtooth;
 - start frequency $f_c = ?$ Hz;
 - duration $T_c = ?$ s;
 - bandwidth $B = ?$ GHz, somewhere in millimeter band (30 – 300 GHz);
 - slope $S = 1\,950\,037\,684\,072.2034\text{ Hz s}^{-1}$.
- number of samples $r = 3202$ over the chirp duration T_c ;
- distance ΔD to the object is approximately 2.3 m;
- slope angle $\alpha = ?^\circ$ (Fig. 1);
- antenna gain is unknown, including the angle of the horn radiation $\beta = ?^\circ$;
- the object parameters:
 - height $h \approx 1$ m;
 - consists of unknown type of plastic with unknown reflectance for millimeter waves.

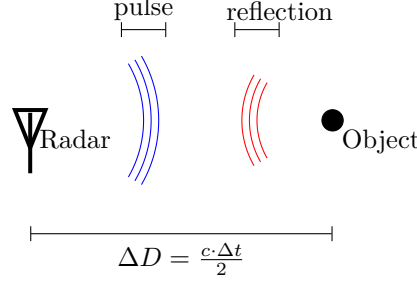


Figure 3: Radar principle overview

3 Radar working principle

In this section we discuss the working principle of a frequency-modulated continuous wave (FMCW) radar that we use in the workshop.

All radars operate with the same basic idea: a wave is emitted and the reflection is collected (see Fig. 3). Then the time difference Δt between wave emission and its reception is computed. As the speed of light c in the space we usually operate (Earth atmosphere) is known, and electromagnetic waves of any frequency always travel with this speed, it is trivial to compute the distance knowing the time difference:

$$\Delta D = \frac{c \cdot \Delta t}{2}$$

Important to note, that we observe a round-trip of the wave, thus the distance obtained have to be divided by 2.

The FMCW radar have the same underlying idea, but instead of one pulse, it produces a "chirp" or a "ramp" (see Fig. 4): a wave of duration T_c , starting with a base frequency f_c , which linearly increases up to frequency $f_c + B$, where B is the radar bandwidth (in Hz). The transmission chirp can be modelled by the equation $F_c(t) = S \cdot (t \bmod T_c)$, where S is a slope or speed of frequency change (thus $B = S \cdot T_c$). This chirp is then reflected from an object, and appear for the receiver as a time shifted original chirp. The reflection can be modelled as a $F_r(t) = S \cdot (t - \Delta t \bmod T_c)$ if $t \geq \Delta t$ else 0, where Δt is a time between start of a chirp and receiving it back (see Fig. 5).

So, in a radar we observe these 2 functions at the same time, but in the end we need Δt . We can find it by subtraction:

$$F_c(t) - F_r(t) = S \cdot t - S \cdot (t - \Delta t) = S \cdot \Delta t$$

Thus in the radar we put a component, called mixer, that outputs $\Delta f = f_t - f_r$, which is the instantaneous difference of transmitted and received waves' frequencies. We use it as a substitute for $F_c(t) - F_r(t)$ part, from which roundtrip time is trivial to obtain via an equation $\Delta t = \frac{\Delta f}{S}$ s. And from this roundtrip time, the distance can be obtained: $\Delta D = \frac{c \cdot \Delta t}{2}$. Or as a complete

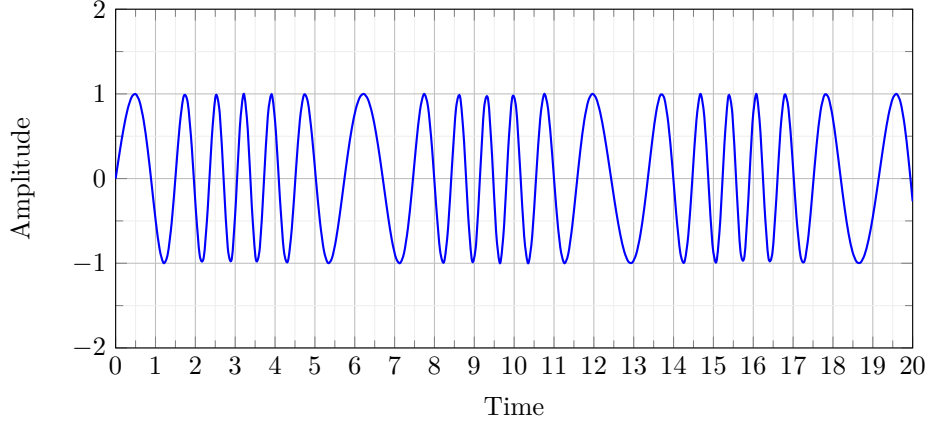


Figure 4: Chirp example (sinusoidal frequency change)

equation:

$$\Delta D = \frac{\Delta f \cdot c}{2S} \text{m}$$

If there are several objects, there would be several waves mixed together (see Fig. 6, an amplitude-time version of second part of Fig. 5), which will arrive at the same time to the radar. As they differ in the distance, the shift is different for all of them, and thus the frequency difference. The mixed signal received is called IF-signal or beat, and by using the Fast Fourier Transform (FFT), we can distinguish their corresponding frequencies in it (Fig. 7 shows frequency components of the wave from Fig. 6) and thus the distances.

The complete procedure for the distance measurement of FMCW radar is:

1. start modulation;
2. record IF-signal for a T_c window;
3. perform FFT;
4. scale obtained FFT frequencies axis with $\frac{c}{2S}$;
5. the result is a dataset with x axis being distance and y being the strength of reflection at this distance;
6. the anomalous spikes indicate higher reflection in the space at the calculated distance, and thus objects.

4 Data processing

Input data of the experiment are 2 sets of 16 vectors of If-signal measurements, each of size 3202. One set contains measurements without the object of interest, and the second one is with the object.

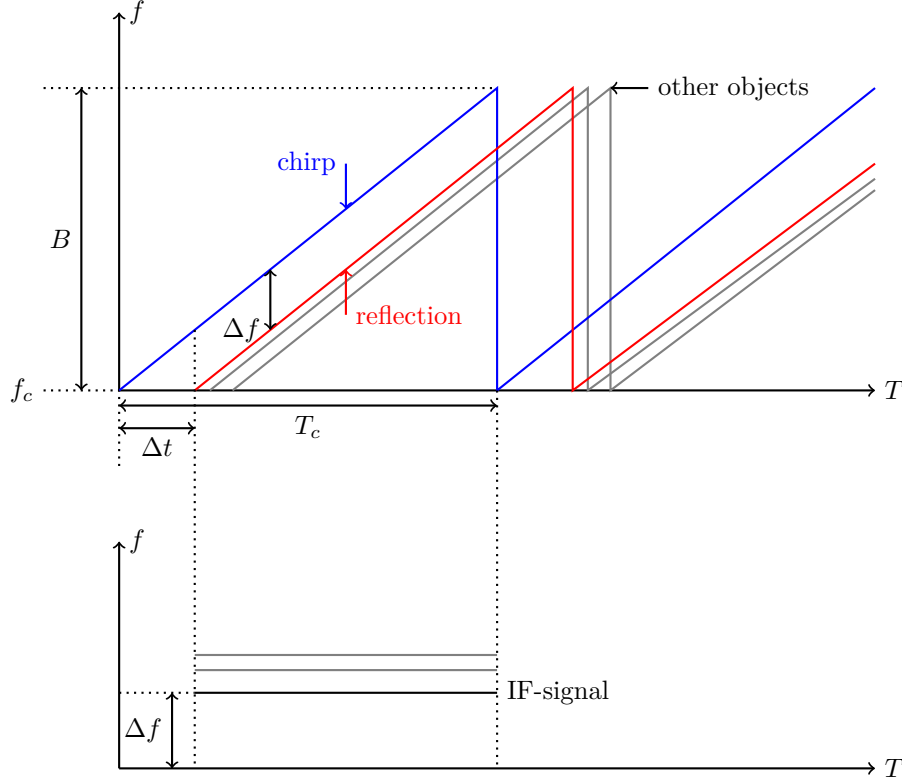


Figure 5: Chirp, reflections and IF-signal frequency tones.

We perform the same procedure described as in the Section. 3, with a difference, that we:

1. average 16 measurements to minimize clutter (random noise caused by environment with non-ideal density distribution, which reflects the waves back, even from air);
2. calculate difference between results of measurements without object with the results with object, in order to remove the environment and highlight the object.

The procedure is implemented in both Rust and Python. The source code is open and available in the following repository: https://github.com/PaulRaUnite/scientific_course.

Considering placement described in Fig. 1, we should expect a spike at around 2.3m, with some other objects that we couldn't control in the real experiment (birds, passing people, etc), i.e something similar to Fig. 8.² This

²The amplitude is assigned arbitrarily.

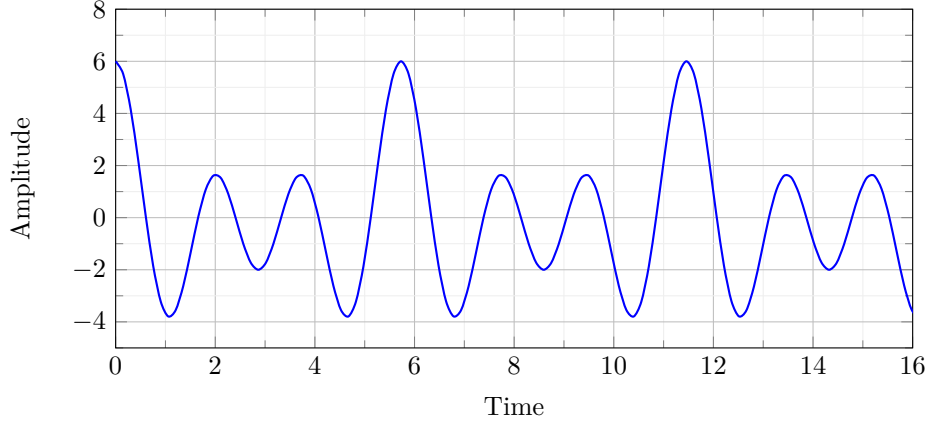


Figure 6: Example IF-signal

does correspond to the result of the experiment (Fig. 9), where we see a spike around 2.3 m.

5 Criticism

There are several factors that influence the precision, cleanness and reproducibility of the experiment. These include:

1. some of the parameters of the radar are unknown (f_c, T_c, B, β) and cannot be inferred from the experiment itself or other parameters, which makes the experiment harder to reproduce;
2. the object is placed on the slope, which adds noise to the input, possibly in a pattern that can show up as an additional object or smear the target object;
3. environment is not fully controlled, and external bodies can enter the area of the experiment freely, sabotaging the results.

6 Conclusion

FMCW radar is a powerful tool that is able to measure distances precisely up to resolution $d_{res} = \frac{c}{2B}$, and to determine a relative speed of the object using the Doppler effect (which is not covered by the workshop). In this workshop we briefly covered the theoretical aspect of its working and we were able to produce code that calculates object distances with the results that match the expected behaviour.

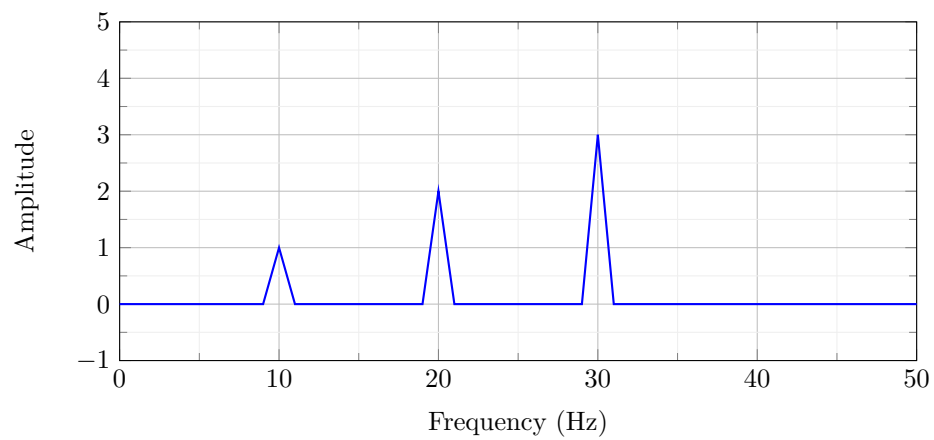


Figure 7: Frequency spectrum of the IF-signal

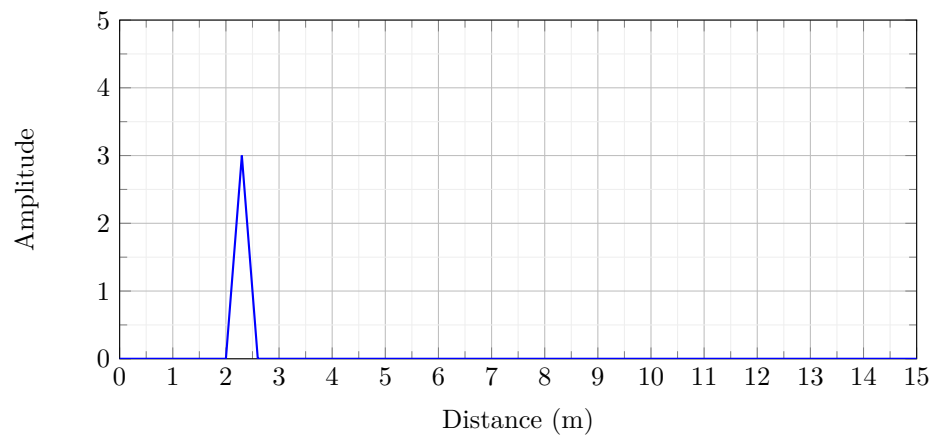


Figure 8: Expected distance data of the experiment

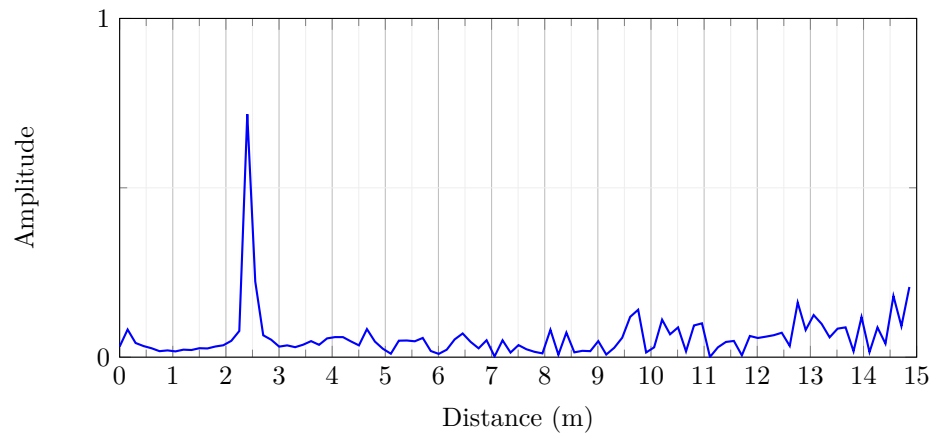


Figure 9: Actual distance data of the experiment