Real Life Radio-Location Examples for Enhanced Signal Processing Teaching

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***Abstract*—For some students, learning signal processing could sometimes be a bit complicated due to the importance of the mathematical background that underlies this field. In this paper, we present two real-life experiments that allows to introduce, in a very natural way, most of the standard tools of signal processing. This teaching, aimed at undergraduate students, is divided in two parts. One exploiting a radar model based experiment, the other designed to process real GPS signals.**

***Index Terms*—Education, Project-Based Learning, radar, sonar, ultrasound, Matlab, navigation, GPS.**

I. Introduction

Explaining what is signal processing to out-of-the-field people is not an easy task [1]. However, one can roughly define it as applying mathematics to real-life measurements in order to improve their interpretation. Hence, it seems natural to teach signal processing starting from its applications in everyday life.

Project-Based Learning (PBL) is a popular example of such a way to teach. PBL is a student-centred pedagogy that involves a dynamic classroom approach through active exploration of real-world problems. Students learn about a subject by investigating a complex question. This active learning method is more attractive for the students and allows them to better comprehend complicated concepts. But it also suffers from many criticisms. Indeed, as student are less guided than in traditional teaching, they generally need more time to reach the goal of the course and it is difficult to ensure that all the fundamental notions have been tackled. As a consequence, it is difficult to measure the knowledge acquired by the students.

In this paper, we present a more guided way to teach signal processing yet still based on real-life applications. More precisely, we gradually present the basic notions of deterministic signal processing based on two popular radio-location applications, namely a RADAR system [2] [3] [4] and the Global Positioning System (GPS) [5]. The signal processing concepts to achieve the objectives of these two projects are presented when needed by the students as they go along their project. This teaching is aimed at undergraduate students who need a refresher on signal processing fundamentals or students having some gaps due to their previous curricula. More precisely, this signal processing class has been constructed for small groups of students (typically between 10 and 20) to interact as much as possible. The signal processing level of these students could be somehow different but they have been selected on their mathematical skills. Hence, they know the majority of the useful mathematical tools, and this teaching has been designed to add a more worldliness meaning. This course has been designed to cover the main signal processing concepts, but can be used to go further on some points for more advanced students. For a complete review of the main signal processing concepts, the students have to tackle the two projects. 6 hours are planned to complete each project while supervised by a teacher.

The paper is organized as follows. Section II presents the radar model used to record signals and the chronological way to introduce the basic signal processing tools needed to reach the goal of the project. Section III presents the second experiment, based on real GPS signals. Once again, we explain how the different signal processing concepts are gradually introduced to get the receiver position. Section IV concludes this paper and gives some feedbacks.

II. The RADAR experiment

A RADAR is an active device transmitting electromagnetic waves. These waves propagate into the surrounding environment and reflect onto possible obstacles. The goal of any RADAR system is to detect these obstacles and to estimate their range, by analysing the received echo waves. For simplicity and cost reasons, we decided to base our system on ultrasound waves and not electromagnetic ones, but it remains very close to real-life radars. Indeed, when using electromagnetic waves, one needs very high frequencies and bandwidth (about hundred of MHz) to achieve a good system resolution. The associated front-end and sampling electronics is complex to realize and the induced computation load is high. To obtain the same range precision, while using ultrasound waves, we can use very low frequencies (some KHz), so that off the shelf electronics is sufficient. Moreover, the amount of data to be processed is low so that a standard PC can be used. The radar model is based on the same components and electronics as the experiments described in [6] [7] and [8]. Such kind of experiments are also described in [9] [10]. We first focus more precisely on the model used to record the

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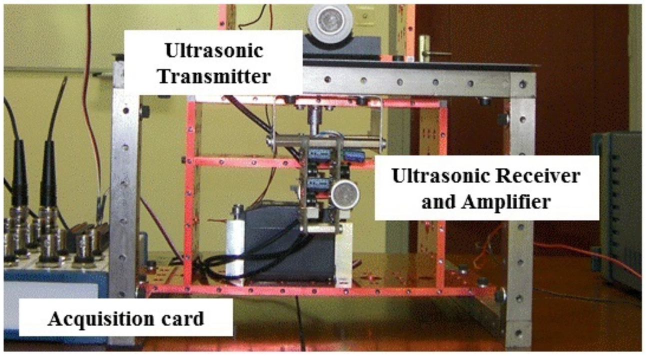

Fig. 1. Model overview

signals, then we present the way we introduce the standard signal processing tools through gradual questions. Indeed, after a brief introduction to radar systems (history, applications) and a presentation of the experiment, a twofold problem is given to the students. First they have to detect and estimate the ranges of static targets. Then, in a second part, they have to design a Doppler frequency filter, known as Moving Target Indicator (MTI) filter, to extract a moving object from all the static echoes (known as clutter). At the end of the project, the students have to write a report which serves as an evaluation to their work.

A. The Radar Model

As shown in Fig. 1, the hardware of the Radar is composed of two $400WB16$ Prowave® ultrasonic wide-bandwidth transducers and narrow bandwidth amplifiers. The central frequency of the system is $f_0 = 40$ KHz and the bandwidth can be tuned from 0 KHz to 4 KHz. The amplifiers are designed to reduce the thermal and environmental noise and supply a $[-5, 5]$ peak voltage to the acquisition card (NiDaq $6064E$). The waveform to be transmitted is directly designed and sent from Matlab.

B. Signal Conditioning

As an introduction part, the students have to answer questions aimed at explaining the different steps used for signal conditioning. Thus, the teacher recalls first the Shannon theorem and the effects of aliasing. Subsequently, the students have to choose the sampling frequency. In order to gain on the sampled data length, aliasing can be allowed. Hence, the students understand that a sampling frequency slightly higher than twice the signal bandwidth is enough in our case. A typical value for the sampling frequency is $F_s = 9.5$ KHz with 4 KHz as a maximum bandwidth. Then the definition of the Fourier transform, its main properties and the Hilbert transform are sequentially introduced. Indeed, the recorded signals from the radar model are all real. For practical reasons, the students have to convert them to their complex counterpart using the Hilbert transform.

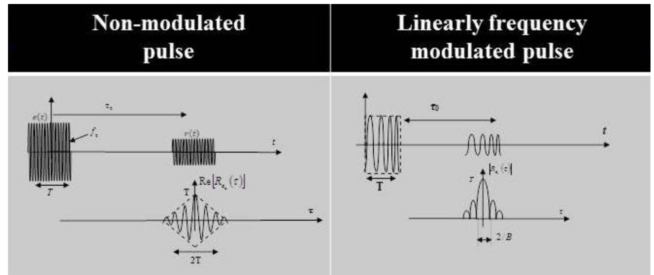

Fig. 2. Relationship between bandwidth and correlation width

C. Static Targets Ranging

Once the signals are sampled, they can be processed by the students, using Matlab. In a first series of tests, we have recorded a radar signal corresponding to the echoes of two closely spaced targets so that they cannot be resolved using a non-modulated pulse. The students will need to use a linearly modulated frequency pulse to detect the two static objects. To complete this objective, the teacher first introduces the concepts of spectral density and self-correlation function as well as their main properties. The relationship between these two functions allows to relate the range resolution to the signal bandwidth. Hence, the students understand the need to use the larger bandwidth, as shown in Fig. 2. They can verify the corresponding range resolution on real data.

D. Moving Target Indicator

In this last part of the project, one target is moving while the rest of the environment remains fixed. The objective given to the students is to implement different high-pass filters (MTI filters) so that one can easily detect the only moving object. To achieve such a goal, a pulse repetition waveform is introduced, as well as the common way of processing in the radar community. As indicated in Fig. 3, the received signal is converted in a matrix where each column corresponds to one pulse. Like this, it is easy to successively and separately process the range, using a correlation on each column and the velocity, using a Doppler filter on each row. The students have to use the Z-transform tool to calculate the transfer functions of the proposed filters and compare their Bode diagrams in order to choose the best filter. They have to compute the corresponding cut-off velocities and to verify the filters behaviours on real data.
All the signal processing reviewed during this radar experiment are gathered together in Fig. 4.

III. The GPS project

The GPS system is composed of 24 satellites orbiting the earth at approximately 20000 km height. These satellites transmit each a characteristic electromagnetic signal. The position of each satellite is precisely known so that any GPS receiver can estimate its position from the received satellites signals. This computation is usually made in two-steps. First, the receiver estimates the different propagation delays from the satellites leading to pseudo-ranges calculation.

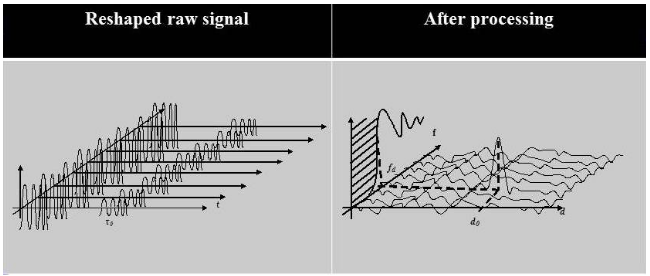

Fig. 3. MTI processing

Part	Project chronology	Concept tackled
Signal conditioning	Converting real signals to complex Sampling (understanding aliasing)	Fourier transform Hilbert transform Complex envelop Shannon theorem
Static targets ranging	Cross-correlation calculation (relationship between bandwidth and resolution)	Auto and Cross-correlation Spectral density FFT
Moving Target Indicator	Analyzing, designing and applying high-pass filters	LTI systems Impulse response convolution Z transform Transfer function Bode diagram

Fig. 4. Radar project chronology and signal processing concepts tackled

Then, the receiver position is calculated thanks to a least square procedure [11].
In this GPS project, we give the students a Matlab data file containing simplified signals. Indeed, the satellites are fixed so that the Doppler effect does not have to be taken into account, as well as the navigation code providing the trajectories of the satellites. The objective is to compute the receiver position. In order to reach this objective, the project is divided into 3 main parts as shown in Fig. 5.

Part	Project chronology	Concept tackled
Receiver analog chain simulation	Demodulation, undersampling, filtering, converting real signals to complex	Fourier transform Hilbert transform Complex envelop Shannon theorem LTI systems Impulse response Convolution Z transform Transfer function Bode diagram
Delays computation	Cross-correlation computation	Auto and Cross-correlation Spectral density FFT
Trilateration	Position calculation, precision	Least Square Minimization

Fig. 5. GPS project chronology and signal processing concepts tackled

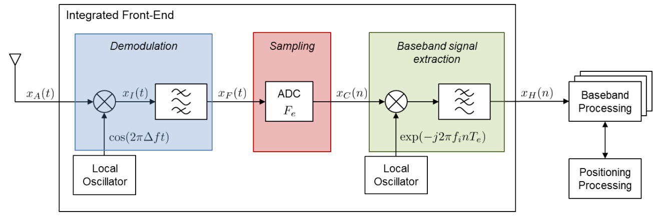

Fig. 6. Analog Receiver Chain

A. Simulation of the analog receiver chain

As presented in Fig. 6, the first stage of the GPS signal processing consists in a demodulation step, an analog to digital conversion and a base-band signal extraction. Unfortunately it is difficult to provide directly analog, high-frequency signals to the students. Hence, the raw data to be processed has been frequency shifted to a lower frequency representing the carrier frequency (40 MHz in our case instead of 1.575 GHz for the actual GPS carrier frequency). Nevertheless the students have to simulate a demodulation step upto 15 MHz, an under sampling and finally a real to complex conversion using the Hilbert transform, as the provided signal is real. This preliminary processing is not, strictly speaking, a part of the signal processing, but allows the student to measure the impact of this signal conditioning onto the final performance.

B. Delays computation

As explained before, the way to compute the receiver position is done in two steps. The first step consists in measuring the time of flight of the different signals to the receiver. The way to proceed is the computation of the cross correlation functions between the received signal and the known transmitted ones, as it has been explained in the radar project. Nevertheless, there are two main differences between the two projects. First, in the GPS signal, we can have upto 24 different signals, whereas we had only one waveform in the case of the radar. Second, we assume that we have only one delay to estimate for each transmitted signals, unlike in the radar case, where several targets can be present. Hence, the concept of resolution, that was a central point for the radar, is less meaningful in the case of GPS. Moreover, as we have a mixture of different satellite signals, a nearly orthogonal signals property is needed in the case of GPS. In this second part, the students have to calculate the theoretical correlation functions (see Fig. 7), check the correspondence on the data, detect the number of satellites present and measure their corresponding delay. Fig. 8 presents an example of such cross-correlation functions with 4 satellites in the field of view of the receiver.

C. Trilateration

Once the different delays have been measured, the last step of the processing consists in computing the corresponding receiver position. At least 4 measurements are needed to estimate the position, as we have a 4-unknowns problem. Indeed, the 3-components of the position vector are unknown

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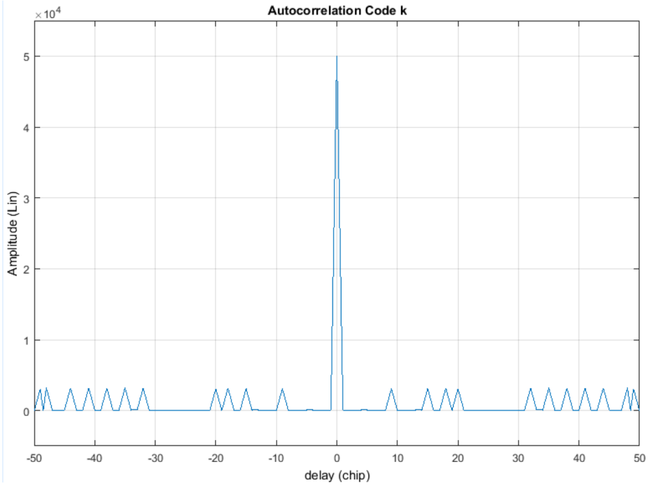

Fig. 7. GPS correlation function

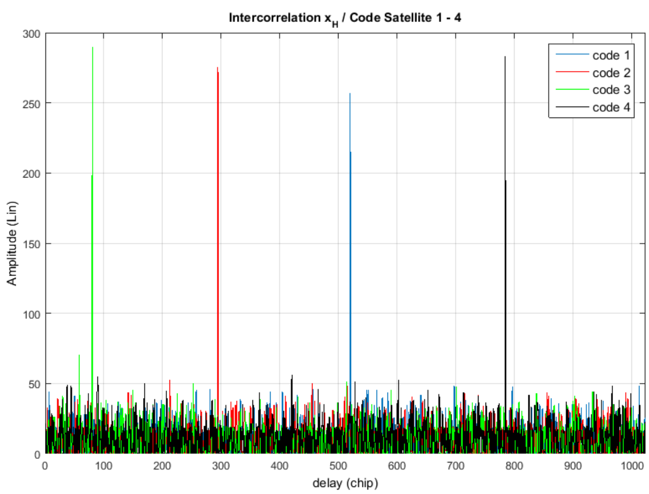

Fig. 8. Cross-correlation example

as well as a clock bias between the satellite time and the receiver time. This 4-dimensional problem is commonly solved in a least-square sense. To simplify its resolution, the non-linear model at hand (1) is linearised near an initial solution, so that the least square solution is closed-form:

$$\tau_k = \frac{||\boldsymbol{p}_k - \boldsymbol{p}||}{c} + \tau_0 \tag{1}$$

where :

- $\boldsymbol{p}$ and $\boldsymbol{p}_k \in \Re^3$ are the positions of the receiver and of the k-th satellite,
- τ_0 is the receiver clock delay with respect to the GPS time reference.
- c is the speed of light.

Near an initial guess position $\boldsymbol{p}_0$,

$$\tau_k \simeq \frac{d_{k0}}{c} - \frac{\boldsymbol{u}_{k0}^T \boldsymbol{\Delta p}}{c} + \tau_0 \tag{2}$$

where $\boldsymbol{\Delta p} = \boldsymbol{p} - \boldsymbol{p}_0$, $\boldsymbol{u}_{k0} = \frac{\boldsymbol{p}_k - \boldsymbol{p}_0}{||\boldsymbol{p}_k - \boldsymbol{p}_0||}$ and d_{k0} is the supposed distance toward the k-th satellite. Or in a matrix form

$$\boldsymbol{\tau} = \boldsymbol{H}\boldsymbol{\phi} \tag{3}$$

where $\boldsymbol{\tau} = [\tau_0 \dots \tau_M]^T$ comprises all the estimated delays, $\boldsymbol{\phi} = \frac{1}{c}\left[\boldsymbol{\Delta p}^T \tau_0\right]^T$ and

$$\boldsymbol{H} = \begin{bmatrix} -\boldsymbol{u}_{00}^T & 1 \\ \dots & \dots \\ -\boldsymbol{u}_{M0}^T & 1 \end{bmatrix} \tag{4}$$

whose solution is

$$\hat{\boldsymbol{\phi}} = (\boldsymbol{H}^T \boldsymbol{H})^{-1} \boldsymbol{H} \boldsymbol{\tau} \tag{5}$$

Given eq. (5), the students have to compute the receiver position iteratively and compare it to the real one.

IV. Conclusions

In this paper we have presented laboratory projects based on two real-life signal processing applications. These experiments allow to easily introduce, in a progressive way, the standard tools commonly used in signal processing. This playful way to teach allows to better understand mathematical tools sometimes complex to catch during traditional courses. Moreover, the students can understand each concept at their pace, as well as learning their application in useful everyday systems.

References

[1] Jose M.F. Moura, "What is signal processing?," *IEEE Signal Processing Magazine*, November 2009.
[2] Merrill Skolnik, *Radar Handbook*, McGraw-Hill Professional; 3 edition, 2008.
[3] Donald J. Povejsil, *Airborne radar*, Van Nostrand, 1961.
[4] Nadav Levanon, *Radar Principles*, Wiley-Interscience; 1 edition, 1988.
[5] Elliott D. Kaplan, *Understanding GPS: Principles and Applications*, Artech House; 2nd edition, 2006.
[6] F. Vincent, B. Mouton, E. Chaumette, C. Nouals, and O. Besson, "Synthetic aperture radar demonstration kit for signal processing education," in *Proceedings ICASSP*, April 2007.
[7] J. Mure-Dubois, F. Vincent, and D. Bonacci, "Sonar and radar sar processing for parking lot detection," in *Proceedings of International Radar Symposium - IRS*, September 2011.
[8] F. Vincent, M. Berranger, G. Beaugendre, and E. Chaumette, "Fire-control radar model laboratory work," in *Proceedings EUSIPCO*, August 2015.
[9] A.J. Camps, "A radar course at undergraduate level: an approach to systems engineering," *IEEE Transactions on Education*, vol. 46, no. 4, pp. 497 – 501, November 2003.
[10] M.A. Jensen, D.V. Arnold, and D.E. Crockett, "System-level microwave design: radar-based laboratory projects," *IEEE Transactions on Education*, vol. 43, no. 4, pp. 414 – 419, November 2000.
[11] Elliott D. Kaplan, *Understanding GPS: Principles and Applications, Second Edition 2nd Edition*, Artech House, 2015.

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