ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

COURSE ENV-542

ADVANCED SATELLITE POSITIONING

LAB 3: ACQUISITION OF GNSS SIGNALS

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1. Acronyms

CAF	Cross Ambiguity Function
FFT	Fast Fourier Transform
GNSS	Global Navigation Satellite System
PRN	Pseudo-random Noise
IF	Intermediate Frequency

2. Goal of the lab

This lab exercise has two main goals. The first goal is to help you understand how the acquisition of GNSS signals is done, and to give you an idea of the processing required. The second goal is to highlight some of the difficulties and challenges encountered during the acquisition of the GNSS signals.

The lab exercise is divided in two parts: the first part introduces you (the student) to the GPS C/A codes correlation properties, while in the second part you will implement a simple acquisition scheme.

3. Information

For each exercise, we provide you a folder with the files to generate the GNSS codes and the templates for the functions to implement.

The Gold codes are 1023-chip long, i.e. 1 ms with a chipping rate of 1.023 MHz.
For a static user, the maximum carrier Doppler for the GPS L1 C/A signal is usually considered to be ± 5 kHz, which means a maximum code Doppler of ± 3.2 Hz.

Important: The files for each exercise have been stored in individual folders. When working on an exercise, remember to set its folder as your Matlab current working folder before running any of the script files. If you don't to do so you are likely to face naming conflict problems.

Here are some useful MATLAB functions:

- load : to load variables from a .mat file,
- plot : to display a 2D graph,
- mesh : to display a 3D graph,
- length : to determine the length of a vector,
- size : to determine the size of a vector or a matrix,
- find : to perform a search inside a vector or a matrix,
- max : to find the value and the position of a maximum inside a vector,
- fft : to perform the fast Fourier transform (FFT).

Important: Please write your answers in this electronic document and document well your Matlab code as you will also need to provide it in a .zip file named as "lab3_LastName_FirstName.zip". The deadline to hand out the .zip file and this document without penalty is one week after the end of this lab, i.e., on April 3th before lunch.

PART I: Introduction to GPS C/A codes correlation

1. Exercise 1: Circular cross correlation

The goal of this exercise is to help you understand the properties of the C/A Gold codes used in GPS signal processing. The correlation properties of the C/A codes allow to measure the delay difference (or code phase) between a locally generated replica and the received signal. In addition, they are fundamental to detect the presence of a signal, or, in other words, "to acquire" the signal.

1.1 Task 1

In this first task you will create a function that computes the circular cross-correlation between two signals of the same length, in this case, two generated PRN codes.

To start, use the function `generateCAcode`() to generate one period of the C/A Gold codes for satellites 4 and 12. Then, create a function `computeCorrelation`() that will compute the circular cross correlation between the two PRN codes.

The circular cross-correlation can be computed as:

$$r[k] = \sum_{n=0}^{N-1} s_1[n]s_2\big[[n+k]\ (\mathrm{mod}\ N)\big] \qquad \text{with } k \in [0, N-1]$$

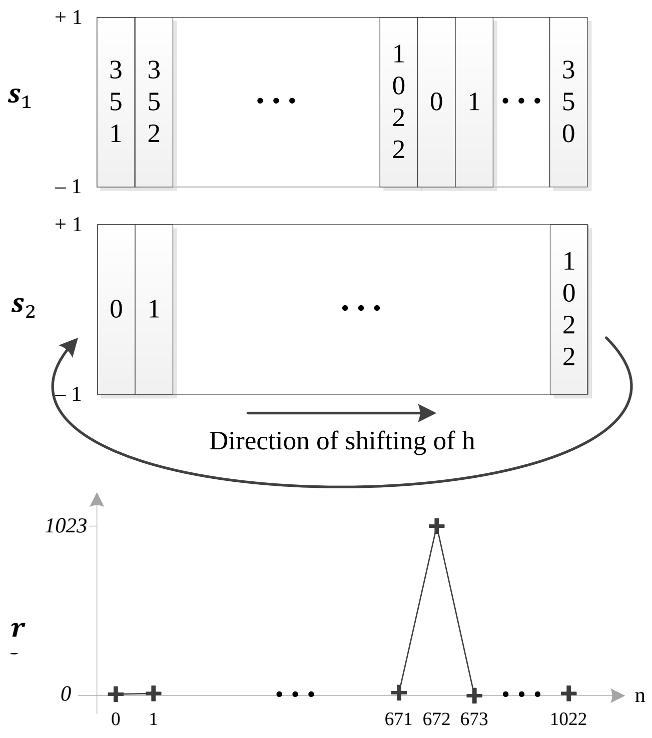


Figure 1 : Illustration of the circular correlation between two PRN codes (the values are in chips)

The template can be found in the file `computeCorrelation.m`, with the following prototype:

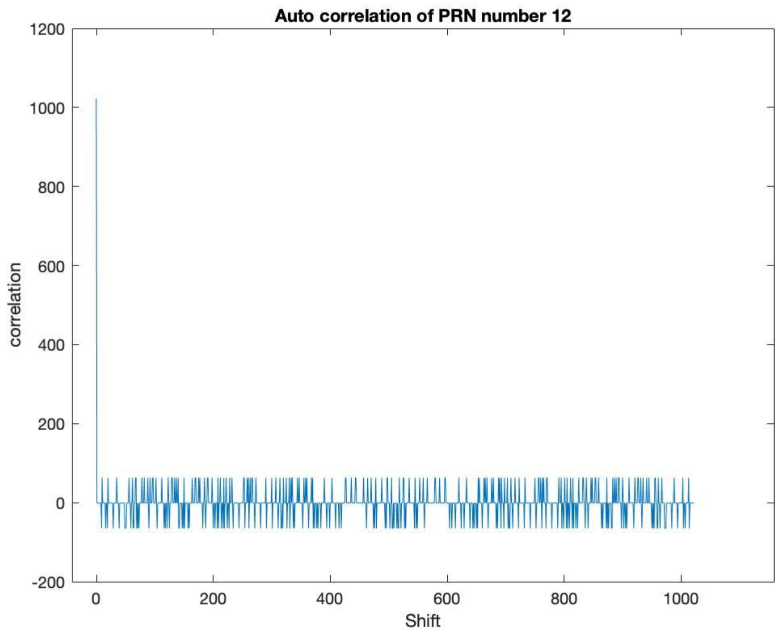
```
function corr = computeCorrelation(signal_1, signal_2)
```

Hint:

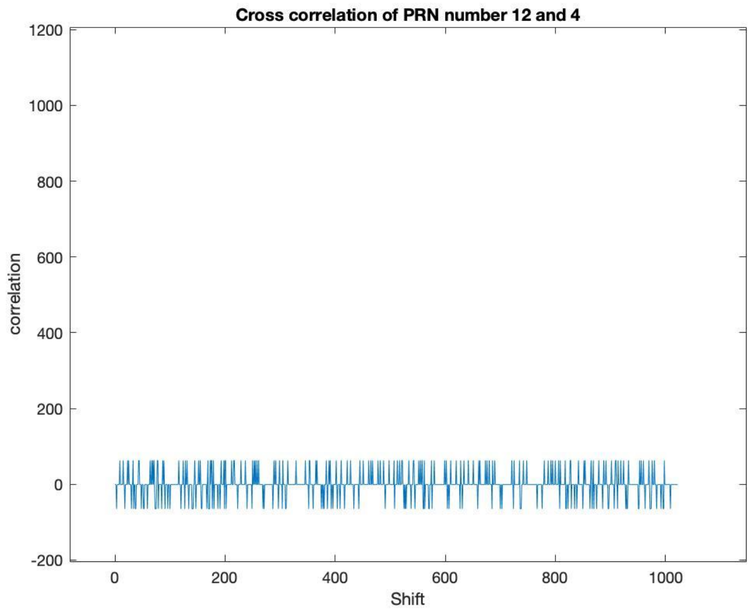
- Use the function `circshift(vector, shift])` to implement the circular shifting.

Finally, test your `computeCorrelation.m` by:

- Computing the auto-correlation for PRN code 12
  (i.e. `computeCorrelation(PRN_12,PRN_12)`) and plotting the results obtained.



- Computing the cross-correlation for PRN codes 4 and 12
  (i.e. `computeCorrelation(PRN_4,PRN_12)`) and again, plotting the results obtained. Use the same scale as in previous plot (e.g. Y-axis [-100, 1100]).



Q.1 Observing your plots, what are the possible values for the correlation of the C/A Gold codes?

When the two signals correlate, we expect a value of 1023, which correspond to the length of the signal.

When the two signals don't correlate, we should expect a zero mean noise, within the interval [-65; 63]

Q.2 The Gold codes are selected as spreading sequences for the signal because of their "interesting" characteristics. The most important characteristics of the C/A codes are their correlation properties. From your plots and the course materials, can you state the two important correlation properties?

The first interesting characteristic is the autocorrelation of the signal with itself. This means that when the signal is aligned with itself, the autocorrelation will produce a peak of amplitude 1023 at zero shift. This allow to calculate the relative shift between the received signal and the receiver code for the computation of the pseudo-range.

The second characteristic is the orthogonality of the different C/A code between themselves, which allow the receiver to distinguish the different satellites, as the cross-correlation of two different C/A code will produce zero mean pseudo random noise with no visible peak.

1.2 Task 2

The file `Ex1T2_mistery_signal.mat` contains a signal composed of the sum of two GPS L1 C/A Gold codes (PRN between 1 and 10) buried in a Gaussian noise, as shown by Eq 1. The signal contains 1 ms of data. The PRN number of these two codes is unknown, as well as their delay (or code-phase) (i.e. τ_a and τ_b both $\in \mathbb{Z}$ in this case).

$$s_{mistery}[n] = c_a[n-\tau_a] + c_b[n-\tau_b] + \eta[n] \qquad (1)$$

The signal has been sampled with a sampling frequency f_s= 6.5 MHz.
The goal of this task is to determine the PRN codes present and their delays.

In the file `Solution_ex1.m`, call the function `computeCorrelation()` to determine visually the PRN codes present in the file `Ex1T2_mistery_signal.mat` and their phase. Fill the following table and add a plot simultaneously showing the correlation results for all the PRNs (1 to 10).

Please, validate your results with the instructor before moving to **Exercise 2**.

<u>Hints</u>:

- Use the function `generateGoldCodeSampled()` to generate the code sampled.
- Use the function `tic` and `toc` to measure the time.

	First code	Second code
PRN number	1	8
PRN Delay (samples)	4086	3368

Q.3 What is the processing time to obtain the correlation for all 10 codes?

The processing time was measured to be 1.131902 seconds. This time also includes the time to find the PRN number of the two codes

Q.4 From your previous results, determine the relative time difference (code delay in s) between the local generated codes and the PRN codes in `Ex1T2_mistery_signal.mat`.

$\tau_a = 0.00062862\, s$
$\tau_b = 0.00051815\, s$

Q.5 What is the width of the main peak (in samples)? How do you explain this?

The full width at half maximum of the peak is 6 samples for PNR number 1 and 8. This is because our sampling frequency fs = 6.5 Mhz is approximately 6.4 times higher than the chip frequency, which means that a shift by ±3 samples still result in a significant correlation as the chip shift is less than one.

2. Exercise 2: Fast Correlation using FFT

The time required to compute the cross-correlation between PRN codes can be relative long. Minimizing this computation time is very important because, during the acquisition stage, the receiver needs to perform correlations with multiple PRN codes with several different carrier Doppler frequencies. In this exercise, we will make a function to perform the correlation faster, and find the codes present in the file `Ex2T2_mistery_signal.mat`, which is a signal composed of the sum of several GPS L1 C/A Gold codes (only PRNs between 1 and 10) buried in white Gaussian noise. The sampling frequency is still 6.5 MHz, and the total duration of the signal is one C/A code period, i.e. 1 ms.

The parallel code phase[1] search acquisition method is used to parallelize the code delay search. Instead of multiplying the input signal with a PRN code with each different code delays to obtain $r[l]$ as done before, the circular correlation can be computed more efficiently in the frequency domain as:

$$\mathbf{r} = \mathrm{IFFT}(\,\mathrm{FFT}(\mathbf{s}_1)\,\mathrm{FFT}(\mathbf{s}_2)^*)$$

where $\mathbf{r} = \left[r[0], r[1], \ldots, r[N-1]\right]^T$ is the correlation vector.

Remark: $\mathrm{FFT}(\mathbf{s}_i)^*$ represents the complex conjugate of $\mathrm{FFT}(\mathbf{s}_i)$, that can be computed using the `conj()` MATLAB function.

Create a function that computes the circular correlation between the input signal and a locally generated PRN code using the FFT. Use the template `FFTCorrelation.m`, with the following prototype:

```
function corr = FFTCorrelation(signal_1, signal_2)
```

Q.6 In the file `Solution_ex2.m`, use the function `FFTCorrelation()` to determine the PRN codes present in the file `Ex1T2_mistery_signal`.mat and their code phase. Do you find the same result as in Exercise 1?
No. The PRN codes we find are the ones from satellites 4 and 9. The code delays are respectively $\tau_a = 0.000736$ s and $\tau_b = 0.00049477$ s.

Q.7 Is the computation faster than in Exercise 1? By which factor? Yes, about 6.5 times faster.

[1] The term "code phase" is equivalent to "code delay".

PART II: GPS C/A Acquistion

The SoftGNSS "reduced" receiver for the ENV-542's course

In this second part of the lab, you will be introduced to the SoftGNSS "reduced" receiver. SoftGNSS receiver is a GPS software receiver implemented in MATLAB based on the open source SoftGNSS v3.0 code developed by Darius Plausinaitis and Dennis M. Akos.

In a non-assisted GPS receiver's cold-start, we need to wait at least 37 seconds until the ephemeris information can be successfully retrieved. Only after that the receiver is able to compute the navigation solution. In order to store 37 seconds of data recorded at a sampling frequency f_S =6.5 MHz, we would need hundreds of megabytes. In addition, depending on the computer, SoftGNSS 3.0 might need several minutes to track 4 channels during 37 seconds. This is not very practical for a course lab exercise.

To overcome those limitations, we decided to use a special stripped down version of the original Soft-GNSS software to be used in this course. In this version of the software, we are able to reduce the required processing time significantly by using some pre-loaded information (i.e. satellite ephemeris, sub-frame start position and TOW) specific for the recorded data.

First step: SoftGNSS "reduced" configuration: `initSettings.m`

The function `initSettings`() creates a data structure with all the settings that the receiver will need to work. To help you, all the fields specifying the required settings have been already defined in this file, so you will only need to modify their values when needed.

Please, read carefully the code comments for each field's description.

Remember to run `initSettings()` function every time you change some of its parameters.

Example of use: `settings = initSettings;`

3. Exercise 3: The acquisition function

The goal of this exercise is to implement `acquisition_1ms()`, a simple signal acquisition function to be used with recorded GPS data, and as part of our SoftGNSS receiver.

We want to implement the parallel code phase acquisition scheme introduced in Exercise 2 following the scheme depicted in Figure 2.

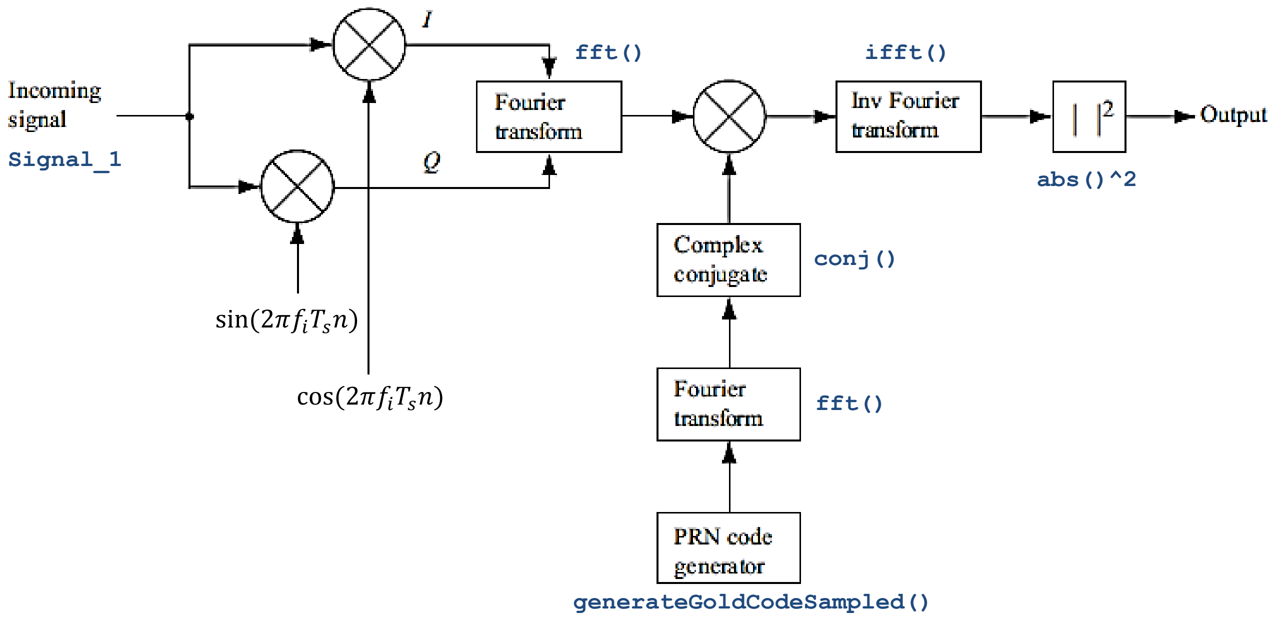


Figure 2: Block diagram of the parallel code phase search algorithm to implement in `acquisition_1ms()`. Figure Source: Kai Borre et. al. "A Software-Defined GPS and Galileo Receiver".

You must complete the `acquisition_1ms()` template function provided:

```
function acqResults = acquisition_1ms(settings, longSignal),
```

where "settings" is the settings structure generated by `initSettings()` and `longSignal` vector contains data input signal.

Do not run `acquisition_1ms()` directly, but instead use the provided script `Main_Ex3.m` to call your function. Remember to set "Exercise 3 – Acquisition" as your MATLAB's working folder before running `Main_Ex3.m`

Follow these steps:

1. You should first create a smaller vector signal_1 from `longSignal`, containing the first 1 ms of data.

2. Generate a 1 ms local replica of the PRN code sampled at $f_s = 6.5$ MHz using `generat-eGoldCodeSampled()` function.

3. As we have seen during the course, the carrier frequency of the received GNSS signals is shifted due to the Doppler Effect, as a consequence of the relative motion between the receiver and the

GNSS satellites. The Doppler frequency shift is a-priori unknown by the receiver. It is part of the acquisition process to find it out by assuming different frequency shift values and trying to detect the signal.

You must generate two carrier signals with a phase difference of 90º (sin and cos) of 1 ms length. The carrier must have a frequency corresponding to the intermediate frequency (IF) $\mp$ the frequency step (`settings.acqFreqstep`) according to the considered search band (`settings.acqSearchBand`).

Hint: you can generate 1 ms carrier signals in MATLAB, use `sin(2*pi*fi*Ts*n)`; where fi is the receiver's IF plus the current frequency offset, Ts is the sampling period $t_s = 1/f_s$, and `n` is an array with numbers from 0 to 6500. Same for `cos()`.

4. Multiply `signal_1` with these local replicas of the carrier frequency to obtain the **I** (in-phase) and **Q** (quadrature) signals.

5. Just like in Exercise 2, perform:

$$\mathbf{r} = \mathrm{IFFT}(\ \mathrm{FFT}(\mathbf{I} + i\ \mathbf{Q})\ \mathrm{FFT}(\mathbf{PRN})^*)$$

6. Finally, take $|\mathbf{r}|^2$.

What you have now is just the code autocorrelation function (ACF) for a certain Doppler frequency shift. You must repeat steps 3 to 5 for all the frequency shifts that you are considering to obtain the Cross-Ambiguity Function (CAF), i.e.:

```
for frqBinIndex = 1:numberOfFrqBins
      Steps 3 to 5
End
```

Figure 3 shows an example of the CAF where the signal is present. As you can see, there is a peak corresponding to the signal delay and frequency shift.

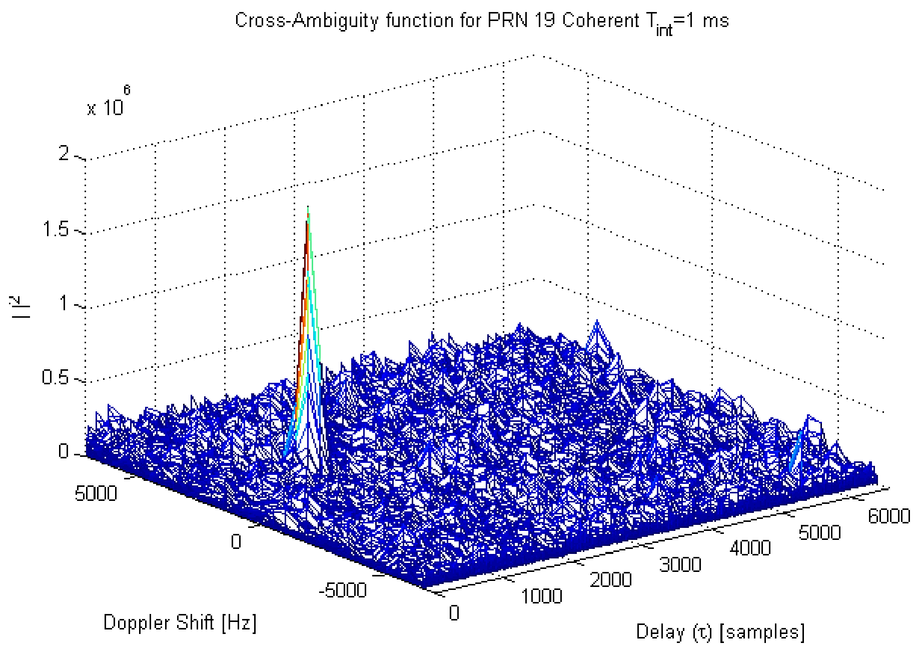


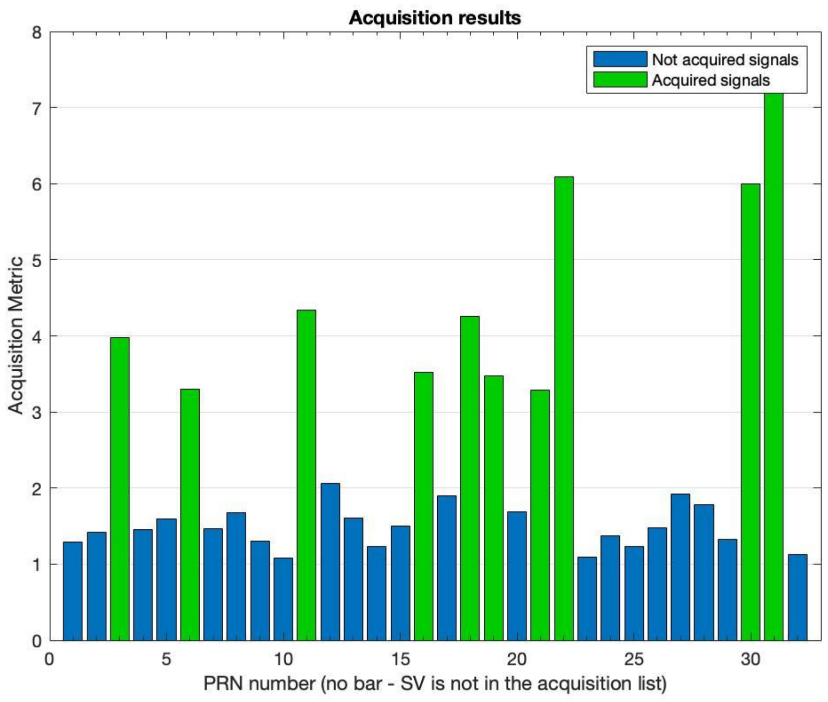
Figure 3: Example of CAF.

7. The last step of acquisition is to identify the position of this peak and determine if it actually corresponds to a signal and not to just noise. To do so you should:

    1. Obtain the CAF value and the position of the highest peak.
    2. Use the provided function `secondPeak()` to obtain the value of the second highest peak on the CAF.
    3. Compare the ratio between the max peak and the second highest peak to `settings.acqThreshold`. If the ratio is above the threshold, we will consider that the signal is present.
    4. If the signal is present, fill `acqResults` as:
        a. `acqResults.carrFreq` = `settings.IF` + Doppler shift corresponding to the max peak.
        b. `acqResults.codePhase` = code phase of the max peak.
        c. `acqResults.peakMetric` = ratio between max and second peak.

Once again, run the script `Main_Ex3.m` to perform the acquisition and obtain the results.

Plot the bar graph that is generated with the acquisition results.



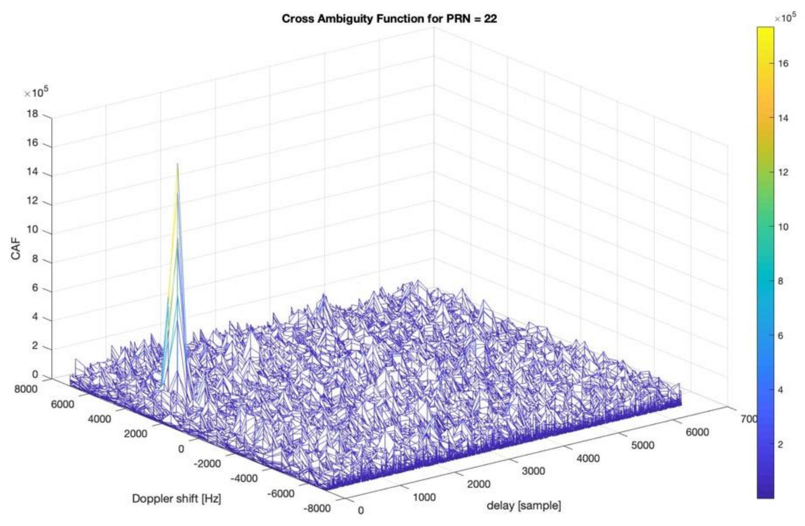
Q.8 How many satellite signals were acquired?

10 satellite were acquired: satellites number 3, 6, 11, 16, 18, 19, 21, 22, 30 and 31.

Q.9 Which is the satellite with the highest detection metric?

From the bar graph, we observe that satellite number 31 has the highest detection metric, with around 7.789.

Plot the CAF function for satellite 22. Use MATLAB's `mesh()` function and don't forget to name figure's axis (use Figure 3 as example).

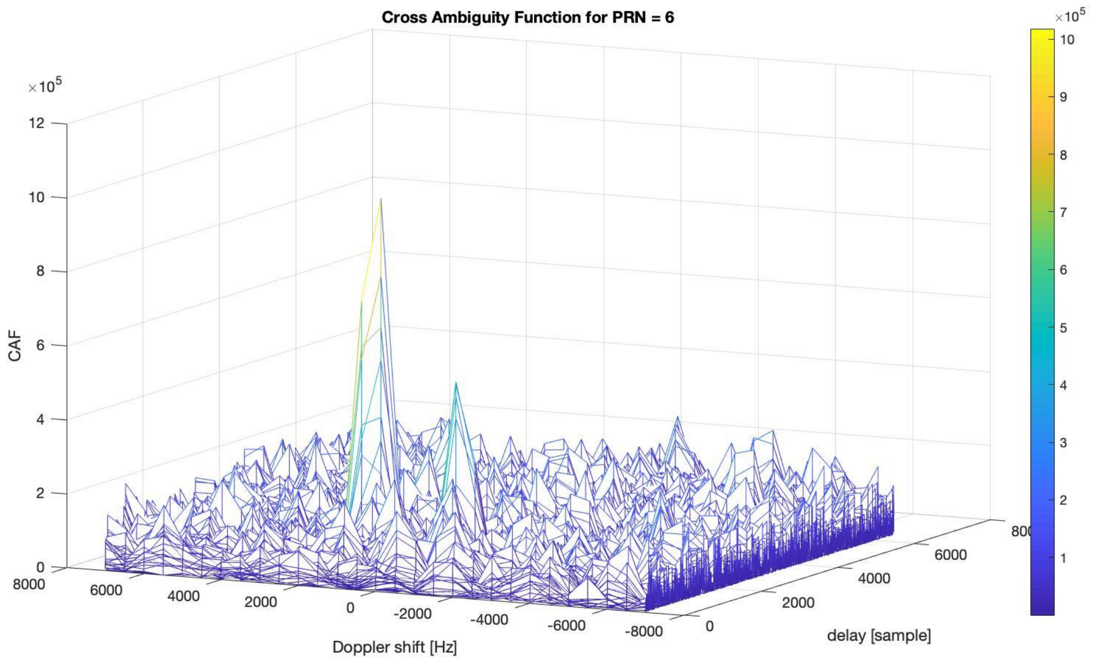


Q.10 What range and step size do you use for the frequency search space? What is the corresponding maximum frequency mismatch loss (check course materials for the definition of mismatch loss)?

In the frequency space, we use a range of 14 kHz and a step size of 500 Hz. The maximum frequency mismatch loss is thus:

$$L = sinc\left(\frac{\Delta f}{2} * T\right) = sinc\left(\frac{500}{2} * 0.001\right) = 0.9003\ or - 0.91\ dB$$

Now plot the CAF function for satellite 6.



Q.11 What do you observe compared with the CAF for satellite 22? How do you explain it ?

Here we observe two peaks in the CAF. This may be due to a data bit transition, so the two peaks correspond to two different bits.

Please, validate your results with the instructor before moving to **Exercise 4**.

4. Exercise 4: High Sensitivity Acquisition

The goal of this exercise is to increase the acquisition sensitivity by increasing the coherent integration time.

To do so, you have two possible options (pick one):

a) Modify the function `acquisition_1ms()`, that you have previously completed for Exercise 3, to implement a 10 ms integration time. In this case please rename it to `acquisition_Tcoh()` function. This is the option we selected.
b) Modify directly `Main_Ex4.m` to include the necessary code to perform the 10 ms acquisition.

If you these two options are not clear for you, please ask the instructor for more details.

In any implementation, the FFTs should still be performed on 1 ms data, and then, the ten results for each individual ms must be summed.

We recommend you to use the `settings.cohInt` (by default = 10) property, in the `initSettings` script, to define the integration time in your code.

Hint: Use `generateGoldCodeSampled()` function to generate 10 ms of sampled code. Then extract the subvectors of 1 ms (from 1 to 10) to compute the correlation with the received signal.

To perform the acquisition and obtain the results, run the script `Main_Ex4.m`. Remember to set "Exercise 4 – High Sensitivity Acquisition" as your working folder before running `Main_Ex4.m`

Q.12 For satellite 22 found in previous Exercise 3, is the peak more or less identifiable than before?

The peak is much more identifiable.

Q.13 Were you able to detect all the satellites found in Exercise 3? What happened to the peak metric?

No, we detect less satellites than previously (only 7). For the satellites we do detect however, the peak metric is much higher.

Are there, any new satellites detected?
If the answer is yes, indicate its/their corresponding code and Doppler frequency.

Satellite PRN number	5	12	25
Code delay (samples)	18	19	8
Frequency Doppler (Hz)	2376	3407	1151

(The frequency doppler is the shift)

Q.14 We have seen how increasing the integration time can increase the sensibility of the receiver for some of satellite signals, while others seem to be not present now. How do you explain this?
Are there any limitations that prevent us to further increase the integration time to acquire even weaker signals? (Consider the GPS C/A case)

This is because of bit transition effect. For some satellites, the peaks, integrated over a longer duration, will balance/cancel each others because of bit transition, so the resulting gain is lower, and thus the signals from that satellites won't be detected. On the other hand, for some other satellites, the peaks will add up and the resulting peak will be higher. So those will benefit from the longer integration time.

Another limitation that prevents the further increase of the integration time is the fact that sequential correlation is not perfect, meaning that the correlation peaks change phase due to relative motions and receiver oscillator drift.

5. Exercise 5: High Sensitivity Acquisition, Bonus Question

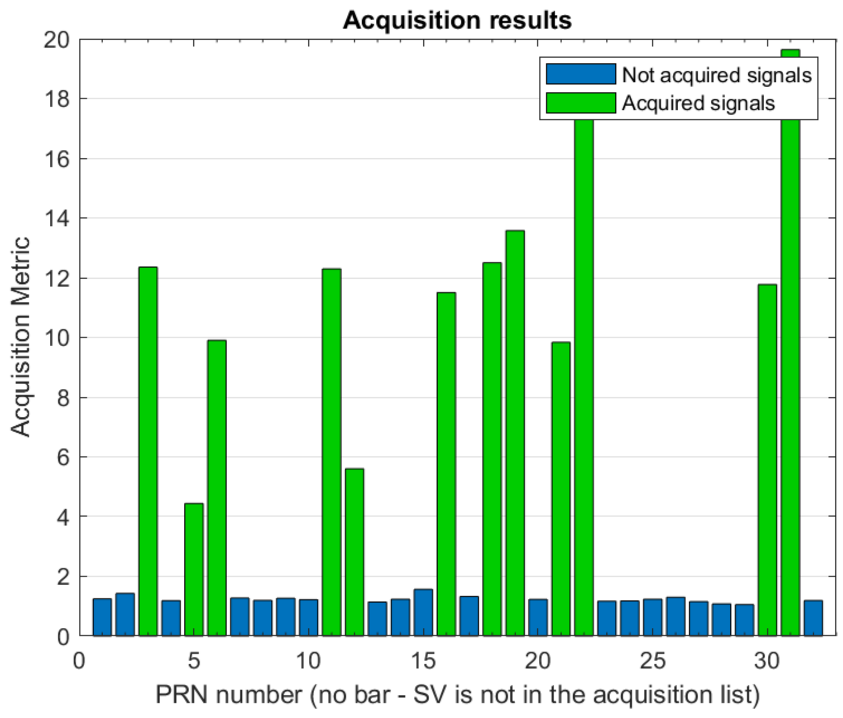
Based on your findings in Q.14, modify your code from Exercise 4 function to circumvent the observed problem.

Once again, remember to set "Exercise 5 - High Sensitivity Acquisition - Non-Coherent T_int 10 ms" as your working folder before running `Main_Ex5.m`

Hint: think about "non-coherent" combinations of intermediate results!

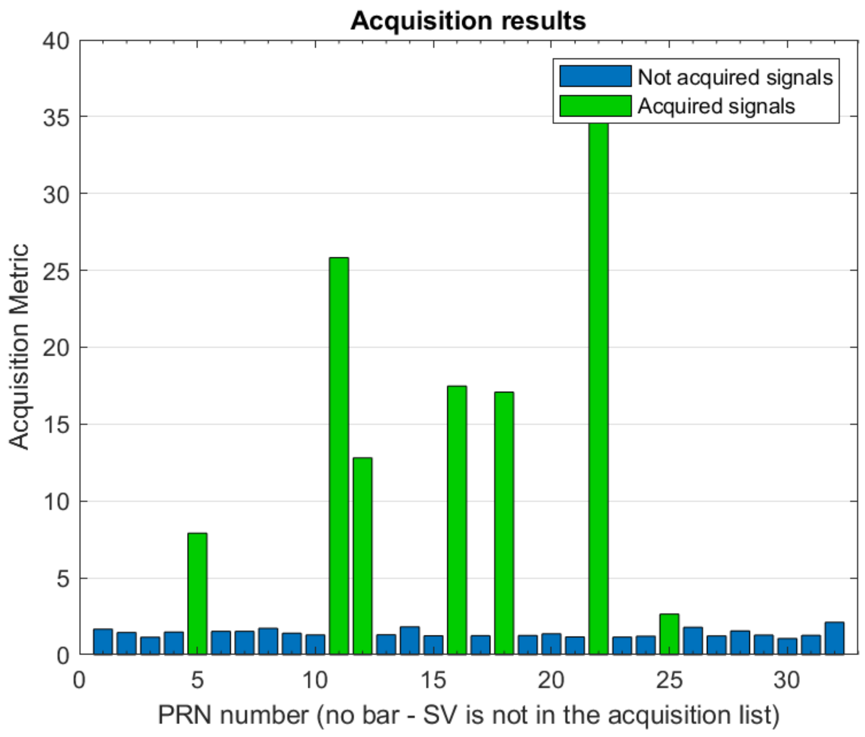
Q.15 Plot the bar graph that is generated with the acquisition results and compare it with the plots that you obtained in Exercise 4 (both with short and long coherent integration times). What do you observe and why?

This is the graph we obtain when considering non coherent integration:



What we see is that first, we acquire more signals than when using long coherent integration time, and even more than using short integration time. Secondly, the acquisition metric is bigger than with short integration time, but smaller than with long integration time. This can be explained by

the fact that most of the time, the received signals are embedded into noise. So when integrating over a longer duration and summing non-coherently, i.e., performing a sum of squares, we also square and accumulate the noise from each signal. (after Root Sum of Square, the noise will have a nonzero mean). So the resulting SNR will be smaller.
Finally, we see here that, as with short integration time, signal from satellite 25 is not acquired.
(Here is the bar graph for exercice 4, just in case)


Acquisition results
Not acquired signals
Acquired signals
Acquisition Metric
PRN number (no bar - SV is not in the acquisition list)