FPGA IMPLEMENTATION OF GPS - L5 ADAPTIVE ACQUISITION

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ABSTRACT

This paper deals with the implementation of an adaptive acquisition stage in a global navigation satellite - GNSS - receiver with a pilot and data channel in case of GNSS L5 signal. Adaptive acquisition decides on GNSS signal presence or absence by comparing a cell under test with an adaptive threshold and provides a code delay and Doppler frequency estimation. Firstly, we introduce an adaptive acquisition with a cell- averaging-constant false alarm rate - CFAR- for pilot channel then we propose a data-pilot fusion. At a second level, the proposed schemes are implemented on FPGA by using system generator and Xilinx tools.Theobtained results are summarized in the resource tables, which show that our implementation is feasible on the selected FPGA card.

KEYWORDS

GPS L5, Acquisition, CFAR, FPGA,Implementation…

1. INTRODUCTION

The first navigation satellites are those of the American project 'Transit'. Complex and voluminous, they performed a sequential treatment requiring a significant calculation time. Thanks to important technological developments, particularly microelectronics, smaller and smaller receivers have been developed for this system and its GPS successor. Currently there are integrated receivers in phones, watches and smart cards, without even noticing them.

During the 1990s, GPS receivers were made using ASICs, slow and expensive development but unsuited to the emergence of new GNSS signals. The solution initially proposed was a software solution, SDR based on the use of microprocessors and generally reserved for baseband processing. This easily reconfigurable solution suffers from limitation in case of parallel processing. FPGA's - Programmable Gate Array - as a component of the SDR receiver is a card that gives us more flexibility, capacity and speed for satellite positioning applications. Technological progress makes possible to produce components ever faster and more integrated, allowing implementationof complicated applications. They are indeed, fully configurable by software’s and they allow physical implementation, by simple programming, any logical function.

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In addition, they are not limited to sequential processing of information as with microprocessors and in case of error they are reprogrammable electrically without having to extract the component from its environment. FPGAs are a compromise between efficiency and flexibility and they provide multichannel parallel processing. These are the reasons that lead us to retain them for our implementation.

A GNSS receiver, in our case GPS L5, consists of several stages where the part requiring the most treatment is the acquisition. It is the latter that we implement on FPGA, while the pursuit and navigation equation resolution can be programmed in microprocessor. In this perspective, we have implemented the acquisition stage according to the theoretical study described bellow for the case of signal L5.

The paper is organized as follows: GPS-L5 signal generation will be presented in section two. GPS-L5 acquisition is presented in the next section, where closed formulas of detection and false alarm probability are derived in case of CFAR detector firstly, than in case of detectors fusion. Implementation results and resources evaluation are presented in sections four and five for Pilot and Data/Pilot channels fusion. These two last sections are followed by conclusion. We note that our principle contributions are to propose an adaptive acquisition stage with CFAR detector then implement.

2. GPS L5 SIGNAL

Civil GPS signals, old ones as well as those corresponding to the modernization phase, are all included in the Ultra High Frequency UHF band and more specifically the 'L' band. These signals result from the combination of CDMA and phase shift keying (PSK) modulation. Civil signals are transmitted on three separate frequencies, L1 (1575.42MHz), L2 (1227.60MHz) and L5 (1176.45MHz). Before modernization, only the L1 signal was available to civilians. Currently two new signals are available although they are not yet transmitted by all satellites. In order to achieve these signals, new modulation schemes have been proposed for the following criteria [40]:

- Minimization of implementation losses at the satellite level;
- Maximizing the power efficiency of satellites;
- Minimization of the level of interference induced by Galileo signals in a GPS receiver;
- Optimizing performance and complexity associated with future Galileo receivers.

L5 is the third civil GPS signal transmitted in the ARNS band; its frequency of 1176.45 MHz is valid only for GPS IIF satellites and the following versions. It is dedicated to life safety applications 'Safety of life applications'. Unlike the previous signals, L5 is composed of two parts: one in phase 'I5' without navigation data denoted pilot channel and another in quadrature 'Q5' with a navigation message of 300 bits length and a bit rate of 100 Hz, noted data channel. Q5 consists of a PRN code of 10230 chips modulated with a Neuman-Hofman code of a length of 20 bits. The code period is 1 ms while the NH20 sequence has a period of 20 ms, therefore, each PRN code is modulated by 1 bit of the NH20 code.

The signal L5 is made according to the diagram of Figure.1, while noting that the navigation message is the same as that sent in L2C. The advantage of having a channel without data is to increase the sensitivity and accuracy of the carrier tracking.

The PRN codes used are generated according to the mimic diagram '2' below, it is noted that 74 codes for I5 and 37 for Q5 are selected from 4000 possible. The rest of the codes are valid for future applications or for possible uses in SBAS. The expression of the L5 GPS signal thus described is given by:

$$S_{L5}(t)=\sqrt{P_{L5}}\begin{bmatrix} D_{L5}(t)\cdot C_{data}(t).NH_{10}(t)\cos(2\pi f_{L5}t-\varphi_{L5}) \\ +C_{pilot}(t).NH_{20}(t)\cos(2\pi f_{L5}t-\varphi_{L5}) \end{bmatrix} \quad (1)$$

where:

P_{L5} : L5 total power ;

D_{L5} : Navigation data ;

C_{data} , C_{pilot} : PRNcodesfor data and pilot channels ;

NH_{20} : Neumann- Hoffman codewith 20ms length.

Figures 3 and 4 illustrate correlation and spectral power density functions respectively. It is observed that L5 has a band of 24 MHz, which requires a higher sampling frequency than L1; moreover, the correlation function is narrow resulting in greater resistance to multipaths.

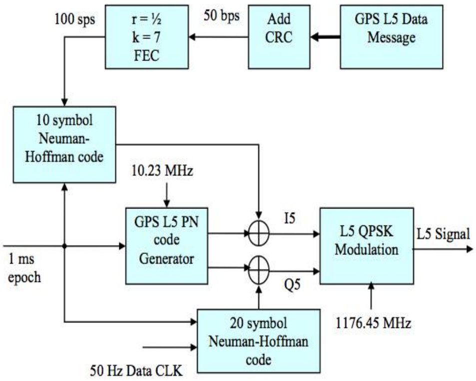

Figure 1. L5 signal generator.

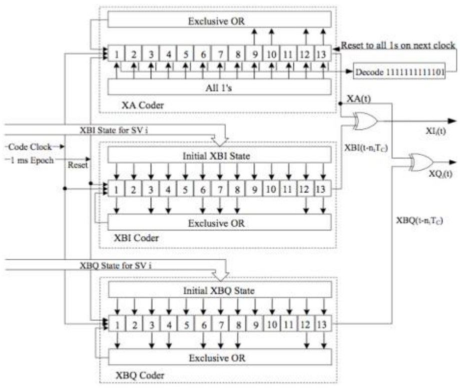

Figure 2. L5 codes generator.

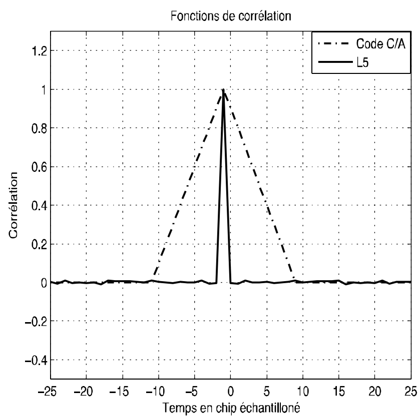

Figure 3. L5 autocorrelation function.

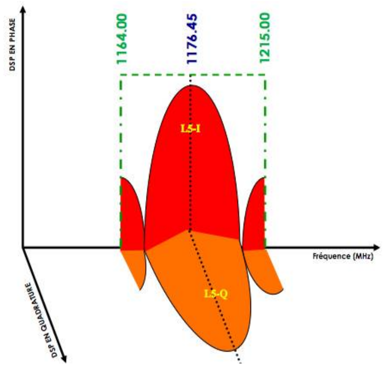

Figure 4. L5 signal *DSP*.

3. GPS L5 ACQUISITION

3.1. Acquisition by Serial Research

Serial research is the simplest and most frequently used method. It consists of correlating the replicas of the codes and the carriers generated locally with the received signal by examining several tests on the code phase and on the Doppler frequency, with a sampling rate sufficiently fine so as not to miss the peak of correlation. The serial acquisition principle is illustrated in Figure 5. GPS satellites are differentiated by 32 distinctive PRN sequences. They are all generated locally; each with offsets ranging from 0 to 1022 chips. Also, in order to find the Doppler frequency of the received signal we sweep the frequency range from FI-5kHz to FI + 5kHz with a 500Hz step, this gives a total number of operations for each code of 1023.41,where 41943 possible combinations.

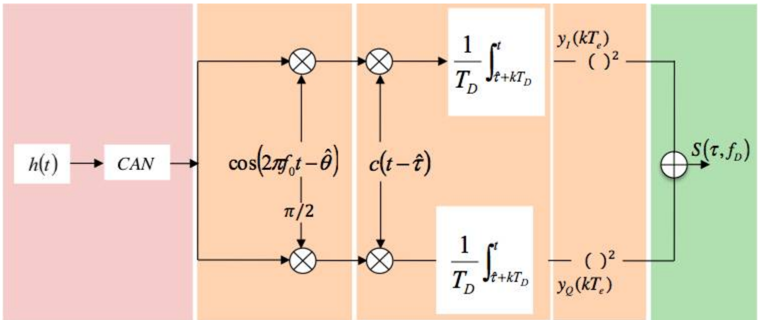

Figure 5.Serial search acquisition.

The expression of the signal at the output of the correlator is given by:

$$y_I(kT_e) = \frac{A}{2}\, d(kT_e)\, \frac{\sin(\pi \Delta f_{dop} T_p)}{\pi \Delta f_{dop} T_p} R_{c_h c}(\tau(kT_e) - \hat{\tau}(kT_e))\, \cos\Big((\theta_0 - \hat{\theta}_0)(kT_e) + \phi\Big) + n_I(kT_e)$$
$$y_Q(kT_e) = \frac{A}{2}\, d(kT_e)\, \frac{\sin(\pi \Delta f_{dop} T_p)}{\pi \Delta f_{dop} T_p} R_{c_h c}(\tau(kT_e) - \hat{\tau}(kT_e))\, \sin\Big((\theta_0 - \hat{\theta}_0)(kT_e) + \phi\Big) + n_Q(kT_e) \quad (2)$$

Also,if the estimated values are correct:

$$y_I(kT_e) = \frac{A}{2}\, d(kT_e)\, R_{c_h c}(0)\cos(\phi) + n_I(kT_e)$$
$$y_Q(kT_e) = \frac{A}{2}\, d(kT_e)\, R_{c_h c}(0)\sin(\phi) + n_Q(kT_e) \quad (3)$$

In the absence of the GNSS signal used or if the received and local codes are not correctly aligned, this last expression contains only noise, namely:

$$y_I(kT_e) = n_I(kT_e) \quad (4)$$

$$y_Q(kT_e) = n_Q(kT_e)$$

While in the presence of the signal, one can write:

$$\begin{aligned} y_I(kT_e) &= \frac{A}{2}\cos(\phi) + n_I(kT_e) \\ y_Q(kT_e) &= \frac{A}{2}\sin(\phi) + n_Q(kT_e) \end{aligned} \quad (5)$$

In addition, we evaluate the cross ambiguity function 'CAF' denoted by 'S' and provided by the serial acquisition after non-coherent integration is given by:

$$S(\tau, f_D) = y_I^2(\tau, f_D) + y_Q^2(\tau, f_D) \quad (6)$$

In the case of GNSS signals composed of data and pilot channels, such as the case of the GPS L5 signal, the same evaluation is carried out, but this time on both channels, which gives in the absence of the signal:

$$\begin{aligned} y_{ID}(kT_e) &= n_{ID}(kT_e) \\ y_{QD}(kT_e) &= n_{QD}(kT_e) \\ y_{IP}(kT_e) &= n_{IP}(kT_e) \\ y_{QP}(kT_e) &= n_{QP}(kT_e) \end{aligned} \quad (7)$$

While in the presence of the GNSS signal:

$$\begin{aligned} y_{ID}(kT_e) &= \frac{A}{2}\cos(\phi) + n_{ID}(kT_e) \\ y_{QD}(kT_e) &= \frac{A}{2}\sin(\phi) + n_{QD}(kT_e) \\ y_{IP}(kT_e) &= \frac{A}{2}\cos(\phi) + n_{IP}(kT_e) \\ y_{QP}(kT_e) &= \frac{A}{2}\sin(\phi) + n_{QP}(kT_e) \end{aligned} \quad (8)$$

3.2. Acquisition with CFAR Detector

Our system analyzed consists of a non-coherent acquisition block followed by a CFAR detector in the form shown in Figure 6. In this figure, the input signal is composed of the message, code, the carrier and of course additional noise. The acquisition processing already described no longer uses a fixed but adaptive threshold of the CFAR type, that is to say a constant false alarm rate whatever the noise variations or even the appearance of multipaths. Many variants of this detector have been proposed in many papers. In our work, we are interested in CA-CFAR 'Cell averaging CFAR'.

Once the established threshold is exceeded according to the CFAR indication, the tracking stage is activated in order to carry out a code and phase tracking; otherwise the locally generated code will be delayed by one value to process the next cell and so on until the decision on the presence or absence of the processed satellite is made.

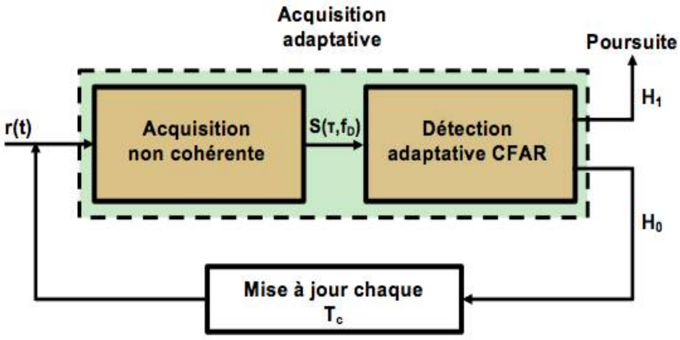

Figure 6. Acquisition with CFAR.

In our work, the CFAR processor is applied at two levels, the first is at the acquisition output of the pilot channel and the second at the output of the data channel. With a proposed analytic expression for detection probability based on the Kummer function, hence:

$$P_d = \frac{1}{\Gamma(M)\left(\sigma_n^2\right)^M 2^{M-1}} \left[\frac{\Gamma(M).\Gamma\left(k, b^2/2\right)}{2p^M \Gamma(k)} + \sum_{l=0}^{M-1} \frac{a^2 b^{2k} \Gamma(M).{}_1F_1\left(l+1, k+1, \left(a^2 b^2 / \left(2a^2+4p\right)\right)\right)}{k!\, p^{M-1} 2^{k-l+1} \left(a^2+2p\right)^{l+1} e^{b^2/2}} \right] \quad (9)$$

with : $k=1,\ p=1/2\sigma_n^2,\ a=\sqrt{T/\sigma_n^2}$ et $b=\sqrt{2.T_c C/N_0}$

${}_1F_1$ is the hypergeometric confluent Kummer function.

$\Gamma(x)$ and $\Gamma(x,a)$ denote the Gamma function and the upper incomplete Gamma function respectively.

3.3. Acquisition with CFAR Fusion

The detection performance can be improved by performing a merger between separate CFAR detectors, this is achieved by maintaining a constant level of false alarms. In order to take advantage of this idea and considering the existence of both pilot and data channels, we propose a CFAR fusion center. In this architecture each detector makes its own decision, the combination is done by an 'AND' rule or an 'OR' rule. In the case of an 'AND' rule, the resulting probability of detection assuming that the two channels are independent, is given by:

$$P_{d\_fusion\_AND} = P_d^2 \tag{10}$$

While the probability of false alarms is:

$$P_{fa\_fusion\_AND} = P_{faP}.P_{faD} = \left(1+T\right)^{-2M} \tag{11}$$

Because the probability of false alarms is the same for both pilot and data channels.

Similarly, using an 'OR' rule, the resulting probability of detection assuming that the two channels are independent, is given by:

$$\begin{aligned} P_{d\_fusion\_OR} &= 1-\prod_{i=1}^{2}\left(1-P_{d_i}\right) \\ &= 2P_d - P_d^2 \end{aligned} \tag{12}$$

The probability of false alarms in this case is given by:

$$\begin{aligned} P_{fa\_fusion\_OR} &= 1-\prod_{i=1}^{2}\left(1-P_{fa_i}\right) \\ &= 2P_{fa} - P_{fa}^2 \end{aligned} \tag{13}$$

4. IMPLEMENTATION OF PILOT CHANNEL

In this section, we are interested in the implementation of the adaptive acquisition stage of the GPS L5 signal. This implementation is linked only to the pilot channel only.

4.1. System Generator

Our implementation is based on a basic block represented by figure 7; this is the non-coherent serial acquisition on a single channel, arranged for implementation by introducing ALU's. This entity consists of:

Inputs:

Signal: Corresponds to the received four-bit quantized GNSS signal;
Local code: This is the locally generated PRN code quantized on two bits;
Cos & Sin: Two locally generated I&Q sinusoidal signals quantized on two bits;
T:CFAR multiplication factor quantized on eight bits.

Sub-modules:

Decoder: The decoder realizes the received signal multiplication by the local GNSS code. At its output the number of bits will therefore be equal to six bits; **Demodulator:** Used to remove the IF carrier from the received signal; based on two locally generated sinusoidal signals quantized with two bits each. The signal at the output is distributed over two channels in phase and in quadrature, each channel is quantized on eight bits;
Integrator: The two outputs from the demodulator are accumulated over thecode length, knowing the multiplication that precedes it represent the correlator implementation. At this level, the number of bits is twenty-five in order to avoid saturation of this module; **Module:** In our acquisition scheme, we opted for a non-coherent integration: it consists of evaluating the module of each channel after integration, but before carrying out this operation we normalized on the code length 'N'. The normalized value is quantized on 26 bits; This module will also allow to combine the two channels in phase and in quadrature by addition; **CFAR:** The signal obtained at the output of the correlator is applied to the input of the CFAR adaptive detector, its parameters are chosen according to the theoretical development presented above. The number of cells is sixteen, which gives a multiplication factor 'T' equal to 0.233345. **Comparator:** In order to decide the presence or absence of a given GPS-L5 code, the correlation samples are compared with the resulting adaptive threshold but after multiplication of the latter with the multiplication factor. If the correlation result exceeds the threshold, the presence of the corresponding satellite is declared.

Outputs:

Output signal: Signal resulting from the acquisition with CFAR;
Threshold: CFAR Adaptive Threshold;
Decision: H0 or H1 for absence or presence of the desired code.

It is noted that the spreading codes used are not implemented but generated under Matlab and then used as inputs at the level of the card. Actually, these codes can be stored in accessible RAM memory during the acquisition operation. Under Simulink / System Generator, our implementation is performed according to Figure 7 in the modular form described above. The execution is carried out for a GPS L5 signal for a delay of 20 chips, a null Doppler and a CNR ratio of 60dB, the result obtained from the 'Scope' tool of the Simulink is presented in figure 8. We observe that our adaptive acquisition stage correctly detects the visible satellite with the corresponding delay.

4.2. Xilinx

The compilation is performed using the ISE tool -version14.1- from Xilinx. This software provides at the end of compilation, various reports and diagrams. Among them, a table of hardware resourcesis given, where a summary of the used physical resources by the system are presented. The Table 1 summarizes the case of our first implementation, where the obtained results show that the available resources allow an implementation on our map.

Table 1.Resources used for single channel.

Resources	Available	Used	Percentage
Slices	37,680	897	2%
Registers slices	301,440	2,476	1%
LUTs slices	150,720	2,399	1%
RAMB36E1	416	0	1%
RAMB18E1	832	0	0%
DSP48E1s	768	30	3%
Inputs / Outputs	600	239	39%
Total time for one period		29,235 ns	
MaximalFrequency		34,206 MHz	

The temporal report provides us with a run time of 29,235 ns per period. Therefore searching on a code will take:

29,235 ns • 40920 chips = 1, 196 ms per execution

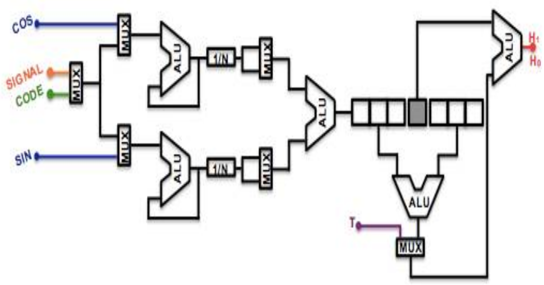

Figure 7.Single channel scheme.

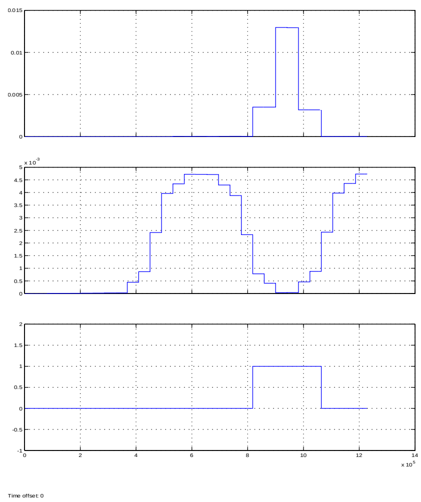

Figure 8.Scope results for a single channel.

5. IMPLEMENTATION OF PILOT/DATA CHANNELS

At this level we are interested in the implementation of the adaptive acquisition stage of the GPS L5 signal based on the fusion of the Data and pilot channels.

5.1. System Generator

We propose the implementation of an acquisition module combining the 'Pilot' and 'Data' channels according to a 'AND' or 'OR' fusion rule. Following the same approach, the implementation is performed according to Figure 9. It should be noted that the difference with the case of the single channel lies in the addition of ‘Data channel’ dedicated to the processing of the code L5Q. In addition, the fusion of the two resulting outputs of the CA-CFAR treatment is performed. A new multiplication factor 'T'' is computed according to expression (12) or (13) which differs from the two fusions rules, indeed, it is 0.240937760751720 for the rule 'AND' and 0.608079762158150 for the 'OR'rule.

For the simulation, we used a signal with its two pilot and data components, therefore the acquisition performed requires the use of two local codes L5I and L5Q for a received L5 GPS signal. Using a GPS L5 signal for a delay of 20 chips, a null Doppler, a CNR of 60 dB and an 'OR' fusion rule, we obtain the result presented on the 'scope' tool of the Simulink and reported by figure 10. We note that the 'Scope' tool operates according to a time scale synchronized with the internal clock of the FPGA. The signal is sampled at 40MHz therefore our delay of 20chips is equivalent on the scope to: $20 \times 10230 \times 4 = 818400 = 8{,}18400 \times 10^5$ samples. Again, we observe that our adaptive acquisition stage detects correctly the visible satellite with the corresponding delay.

5.2. Xilinx

In Table 2, we present a part of the summary resources given by Xilinx compilation. The obtained results shows that the available resources allowed us to implement the proposed acquisition on our FPGA card.

Table 2. Resources used in Pilot / Data channels.

Resources	Available	Used	Percentage
Slices	37,680	1,521	4%
Registers slices	301,440	5,256	1%
LUTs slices	150,720	5,051	3%
RAMB36E1	416	0	0%
RAMB18E1	832	0	0%
DSP48E1s	768	60	7%
Inputs / Outputs	600	225	37%
Total time for oneperiod		30,869 ns	
MaximalFrequency		32,395 MHz	

Regarding the time ratio, we obtained a run time per period of 30.869 ns. Therefore searching on a code will take:

30,869 ns × 40920 chips = 1, 263 ms per execution

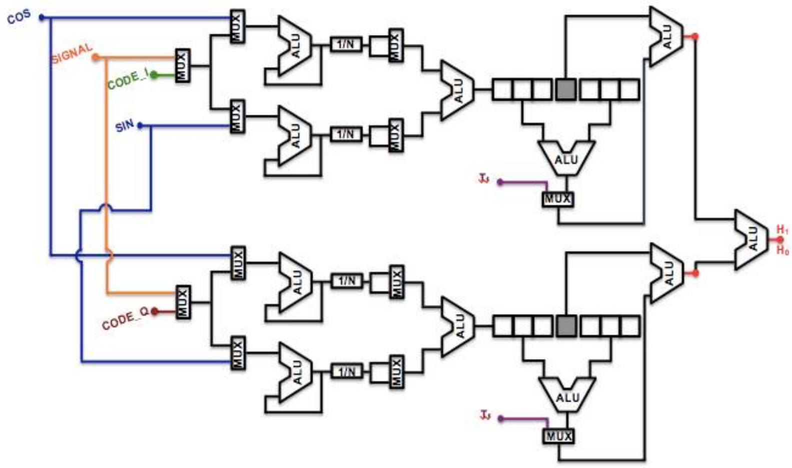

Figure 9.Pilot/Data channels scheme.

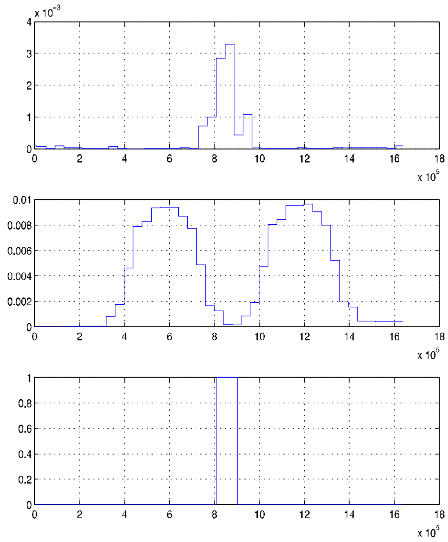

Figure 10.Scope results for a Pilot/Data channels.

6. CONCLUSIONS

In this paper we have proposed an implementation approaches of an adaptive non-coherent acquisition with CFAR threshold dedicated for GPS L5 signal, on FPGA. First, an analytical closed form expression of the detection and false alarm probabilities for the CFAR detector and for the fusion center, have given. Second, we have proposed two implementations approaches; the first approach is about the signal channel acquisition and the second is about the Pilot/Data channel case. The implementations are carried out in two stages, in Simulink / System generator simulation then under Xilinx. The BitStream codes are generated successfully. The implementation results show the feasibility and the efficiency of the proposed approaches.

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