DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

Ecole Nationale Polytechnique

Electronic Departement
Laboratory of Communication and Photovoltaic Conversion

In partial fulfillment of the requirement for
Engineer's Degree

Design and Implementation of GPS Disciplined Oscillator

Youcef BOUKHELKHAL
Djamal CHAIB

Supervised by

Mr. Bachir TALEB PhD. Mourad ADNANE

Presented in public on : 17th June 2017

Jury members:

President	Mr. A. BELOUCHRANI	Professor	ENP
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Supervisors	Mr. M. ADNANE	PhD	ENP
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ENP 2017

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Dedication

I would like to offer this work to my dear mother, who always has been there for me during my entire curriculum.

I would like to dedicate this work to my father also, who is a great source of inspiration for us, who took care of us during all these years.

I would like to mention my older sister MAISSA and my little brother Sidahmed and my grand-mother, not to forget all of my friends in POLYTECH and outside.

,Djamel

This work is for everyone that supported me, beginning with my mother and my father: who took care of me since my childhood till this day.

This work is for my little sisters: may they accomplish much more than this.

I would like to dedicate this work to my grand-parents, and all of my family. also to my cousin Oussama, who I consider as my only brother.

And finally, I would like to thank all my friends whom I met at every stage of my education, and every stage of my life.

Sincerely, Youcef

Acknowledgment

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We would like also to thank Dr Mourad ADNANE for his availability, his precious advices during the thesis, we learned a great a deal from him, not to forget his good humor and kindness.

Our sincere thanks to the committee members for reviewing our thesis and for their advices and insightful comments.

Special thanks to Mr. Peter Putnam who made his great expertise in the field available to us at a moment's notice and replied to every single question we had with great passion and in exquisite detail.

CHAIB Djamel / BOUKHELKHAL Youcef
ALGIERS - 2017

Abstract

ملخص:

الدقة في التردد هي أمر بالغ الأهمية في تطبيقات الاتصالات السلكية واللاسلكية (الارسال و الاستقبال) وخاصة في القياسات ، والأجهزة التي تحقق دقة تردد جيدة تكون اما باهظة الثمن أو غير متوفرة. يدخل عملنا في اطار تصميم وتحقيق مذبذب الذي تسيطر عليه إشارات *GPS* يسمى *GPSDO* ، *GPSDO* يعطي تردد ذا دقة عالية بسعر جد معقول.

الكلمات الدالة : تردد ، مذبذب ، دقة ، إشارات *GPS* ، تصميم

Résumé:

Le réglage en fréquence est d'une importance primordiale dans les applications de télécommunication (mesure, émission et réception), et les appareils permettant d'atteindre une bonne précision en fréquence sont soit chers soit non-disponibles. Notre travail consiste en la conception et la réalisation d'une base de temps en utilisant un récepteur GPS pour la piloter, et ainsi avoir une très bonne précision pour un prix relativement bas.

Les mots clés : fréquence , oscillateur , précision , signaux GPS , conception. Abstract:

The frequency accuracy is very important in the telecommunication field, it covers a whole spectrum of applications (measurement, data transmission), and the devices that have accurate clocks are very expensive and nearly unavailable. Our project consists in the design and implementation of a device GPSDO that is an oscillator controlled by GPS signals, the GPSDO yields a very accurate frequency for a very affordable price.

Key words : frequency , oscillator , precision , GPS signals , conception.

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Acronyms

A/D : Analog to Digital.
AGC : Adjustable Gain Control.
BIPM : Bureau International des Poids et Mesures.
DGPS : Differential Global Positioning System.
DSP : Digital Signal Processing.
DTCXO : Digital Temperature Control Crystal Oscillator.
EEPROM : Electrically Erasable Programmable Read Only Memory.
EFC : Electrical Frequency Control.
GGA : Fix Data.
GLONASS : Global Navigation Satellite System(Russia's version of GPS).
GPIO : General Purpose Input/Output.
GPRMC : Recommended Minimum Data for GPS.
GPS : Global Positioning System.
GPSDO : GPS Discipline Oscillator.
GSM : Global System for Mobile communication.
IF : Intermediate Frequency.
LED : Light Emission Diode.
LNA : Low Noise Amplifier.
LO : Local Oscillator.
N/C : Not Connected.
NIST : National Institute of Standards and Technology.
NMEA : National Marine Electronics Association.
OCXO : Oven-Controlled Crystal Oscillator.
OEM : original equipment manufacturer.
PLL : Phase Locked Loop.
PPS : Pulse Per Second.
RF : Radio Frequency.
RMC : Recommended Minimum Data.
ROM : Read-Only Memory.
SMA : SubMiniature version A.
SMB : SubMiniature version B.
SRAM : Static Random Access Memory.
SV : Space Vehicle.
TCXO : Temperature Controlled Crystal Oscillator.
TMARK : 1pps time mark.
USD : United States Dollar.
USNO : United States Naval Observatory.
UTC : Coordinated Universal Time.
VCO : Voltage Controlled Oscillator.

INTRODUCTION

Any lab, engineering test area, or manufacturing test or field of telecommunication has a potential need for stable precise frequency reference essentially for calibration, synchronization.

The accuracy of devices that contain internal oscillators degrades over time, this frequency drift or inaccuracy is typically caused by electric or mechanical shocks or environmental factors, besides circuit components accuracy drift, temperature and humidity. A typical setup for calibration involves connecting the 10 MHz sine wave output from the primary frequency standard to the device we wish to calibrate, that way the frequency accuracy is improved through external input frequency.

Different fields of telecommunication require a stable and precise clock to ensure a good functioning within, for instance, if one has a wide local network and he needs its equipments to work at the same phase (synchronized), in this case using several synchronized oscillators with accurate clocks is needed[4].

One of the most important aspects of a sensor measurement system is the degree to which you can correlate in time the data acquired from multiple channels. If your data is not appropriately correlated in time, or synchronized, then your analysis and conclusions from your test data are inaccurate, for this purpose many equipments have external input references of 10MHz frequency, connecting the external frequency reference in these equipment improves stability and measurement accuracy.

The aim of this work is to develop a device that has this features and that satisfies the requirements mentioned above.

Chapter 1

Time Reference Overview

1.1 Introduction

There are many types of oscillators: relaxation oscillators, sine wave oscillator, multivibrators, and so on, since they do not present very stable clocks, thus they can not be seen as time references.

Another type of oscillators called “atomic clocks” such as cesium and rubidium oscillators: these are crystal base oscillators with very specific features that allow them to yield a very precise frequency, these oscillators are more likely to be used as a time references[1].

There is yet another type of oscillators that uses a crystal named “the quartz”, the engineering of these oscillators is complex since it takes into account external factors (temperature, humidity), they are often called TCXO (temperature compensated oscillator) or OCXO (oven controlled oscillator) [5].

These oscillators when combined to a GPS properly can give a high precision clock, and this is what our project is about.

1.2 Time reference types

1.2.1 Atomic clocks

An atomic clock is a clock device that uses an electronic transition frequency in the microwave, optical, or ultraviolet region of the electromagnetic spectrum. The principle of operation of an atomic clock is based on atomic physics; it uses the microwave signal that electrons in atoms emit when they change energy levels[6].

Cesium oscillator

Only the cesium oscillator (Figure 1.1) is currently defined as a primary frequency standard, its frequency does not change with time, but the cost is a major issue, the initial purchase price of a cesium oscillator ranges from $30,000 to $80,000 , they are used in calibration laboratories, GPS satellites and GPS base stations.

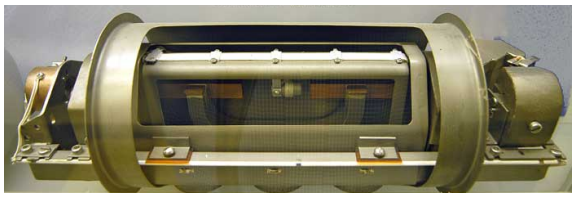

Figure 1.1: Cesium beam tube

Rubidium oscillator

Rubidium atomic clocks (Figure 1.2) are not primary standards, their frequencies change in time due to internal and external influence sources, their typical accuracy is normally about 1000 times worse than a cesium if they are not adjusted and the price of a rubidium oscillator goes from $3000 to $8000, They perform much better than a quartz oscillator and cost much less than a cesium oscillator,they are used in calibration laboratories, GPS satellites and some professional equipments.

Figure 1.2: Rubidium oscillator

1.2.2 Quartz Oscillators

Quartz Oscillators consists of a mechanical oscillator it exists in many devices due to its low cost and reduced size, frequency accuracy of quartz oscillators is sensitive to changes in temperature, so the most stable devices enclose the quartz crystal in a temperature controlled oven. These devices are known as OCXOs [5].

OCXOs (Figure 1.3) often have excellent short term stability and a low phase noise characteristics, their simple design makes them very reliable. However, their accuracy can change rapidly due to frequency drift or aging.

Figure 1.3: oven controlled quartz oscillator

Quartz oscillators meet the needs of countless applications, but the large variations in their frequency over the long term make them a poor choice as a frequency standard.

1.2.3 The GPS disciplined oscillator

We noticed through our research that we basically have two choices when it comes to high precision oscillators: we have on the one hand an atomic clock oscillator (cesium, rubidium) that yields the best precision but its high cost makes it unaffordable for most laboratories[1]. On the other hand we have the OCXO (oven controlled crystal oscillator) which is affordable and can be controlled through a voltage input but it is not accurate enough for professional use, so how to get the best of both worlds?

The idea is to use a technique to combine the two; this technique is named GPSDO which is quite affordable and has good performances. The GPSDO consists of an oscillator with high short term frequency precision (OCXO, Rubidium, TCXO) that can be controlled through a narrow range around 10Mhz, it uses a reference signal that comes from atomic clocks on the GPS satellites to adjust it.

1.3 The criteria that define a good time reference

1.3.1 Traceability

Is when a measurement is linked to known standards which have a better accuracy through an unbroken chain[7]. In our case let us take a look at the traceability chain for a GPSDO (figure 1.4).

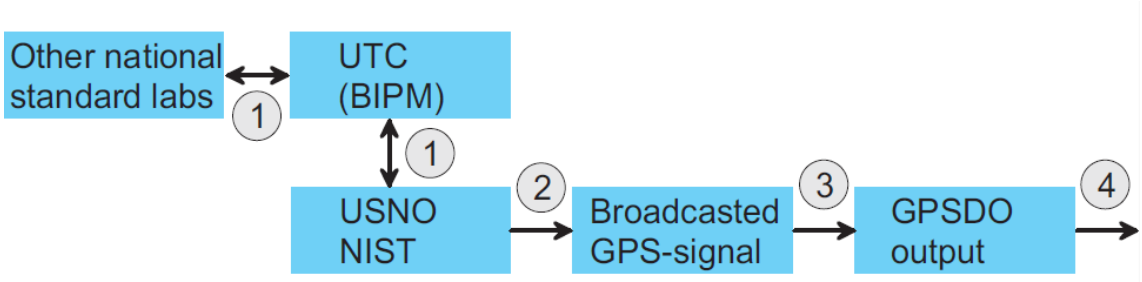

Figure 1.4: traceability chain for a GPSDO

The international SI-definition of the unit of time, 1 s, is the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the cesium atom, it means the cesium atomic oscillator has the highest order of accuracy, its typical relative frequency uncertainty is in the order of 10^{-12} , the average of multiple cesium oscillators can reduce the uncertainty to the order of 10^{-13} or better. The secondary standards like Rubidium or quartz crystal oscillators need to be periodically calibrated against a better standard which is traceable to a Cesium standard[7].

The international time standard UTC (Coordinated Universal Time), which is administrated by the BIPM(bureau international des poids et mesures), is the average time between more than 200 primary standards in the world .

The GPS-satellite signals are traceable and controlled by the USNO (US Naval Observatory) (link number 2 in the Figure 1.4) whose master clock is continuously monitored by NIST (National Institute of Standards and Technology). Both NIST and USNO contribute to UTC and also they are traceable to it (link number 1) , then comes link number 3 which is the link between the output of the GPS-receiver and the broadcasting signals from the GPS satellites. The output of the receivers are generally 1pps (pulse per second), but the GPS module (TU30D140) has an output of 10Khz for more accuracy, uncertainty of this output is made by multiple factors which are explored in the next chapters. And finally the link number 4 is how much the local oscillator is disciplined to the GPS receiver.

The disciplining process is affected by the uncertainty of the used circuitry ,the local oscillator (simple crystal oscillator to high accurate rubidium oscillator) and by the factors which can be controlled to certain limited level.

The uncertainty of the whole chain is related more to the links number 3 and 4 because the uncertainties of link number 1 and 2 are very small compared to the other 2 links and thus can be neglected.

Due to the transfer standard from UTC to our GPSDO (Figure 1.4), GPSDO can be used as a secondary frequency standard for calibration or other purposes, if it is verified and documented by official calibrating institute.

1.3.2 Frequency accuracy

Actually the frequency accuracy has the same meaning as time or clock accuracy because if an error appears in the time period it will definitely appear in the frequency[7], and this accuracy is represented by different physical characteristics, in general it can be divided in to two main aspects, long term stability and short term stability.

Long term stability

The long term stability defines the maximum frequency offset uncertainty to UTC, if we say a $10MHz$ oscillator has an uncertainty of $\frac{\Delta f}{f} = 0.01$ it means its frequency is between $9.95MHz$ and $10.05MHz$.

The long term stability also defines the frequency aging, the rubidium oscillator has an aging of 5×10^{-10} per year that means the frequency can change by 5×10^{-10} in one year.

Short term stability

It represented by, phase noise, jitter, and Alan deviation.

Phase noise:

phase noise is a sensitive characteristic for small term stability it define how noiseless the system is, it defines also the variations in the timing of its zero crossings from cycle to cycle, we can see it as the frequency drift in the smallest scale (or one period).

This small variation caused by external noise adds to the signal phase, if we model the signal by the equation 1.1

$$S(t) = \cos(2\pi f_0 - \phi(t)) = \cos(2\pi f_0)\cos(\phi(t)) + \sin(2\pi f_0)\sin(\phi(t)) \qquad (1.1)$$

where $S(t)$ is the signal , f_0 is the main frequency and $\phi(t)$ is the phase noise.

And we assume that $\phi(t)$ is very small, it gives 1.2

$$S(t) = \cos(2\pi f_0) + \sin(2\pi f_0)\phi(t) \tag{1.2}$$

The result is the original signal plus a modulated noise with the main frequency and the influence of that noise can be shown in its spectrum.

Phase noise is expressed in units of dBc/Hz (decibels relative to the carrier per hertz) , and it is the power ratio of $1Hz$ bandwidth located in certain offset frequency from the carrier (noted by P_{SSB}) to the power of the signal (P_S) as the formula 1.3 shows.

$$PN(f_m) = P_{SSB}(f_m) - P_S \tag{1.3}$$

the phase noise function depends on the frequency offset f_m as the figure 1.5 shows.

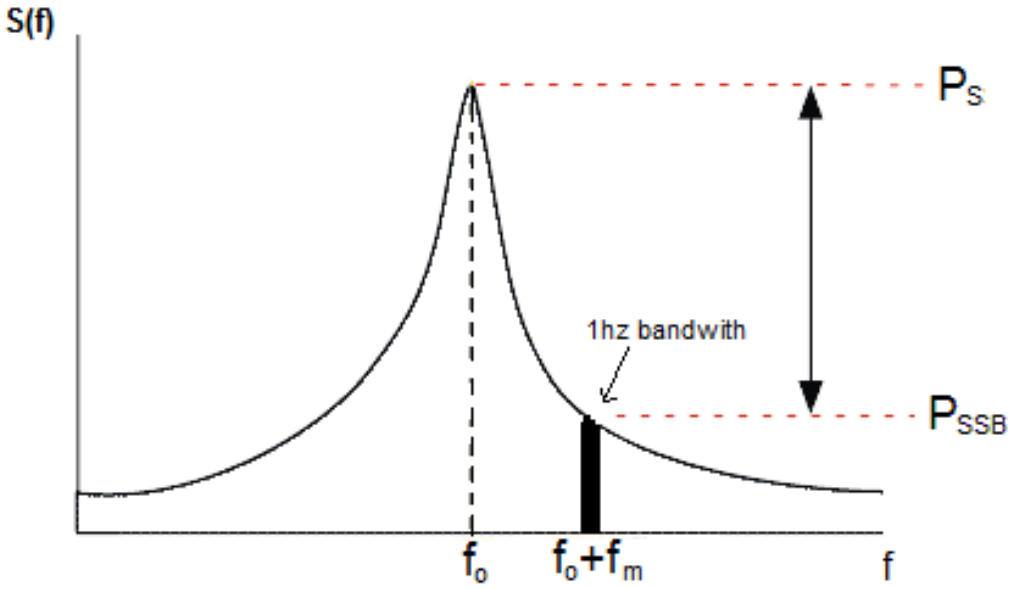

Figure 1.5: Phase noise

Jitter:

The jitter is a version of phase noise for a digital signals or square wave signals (Figure 1.6).

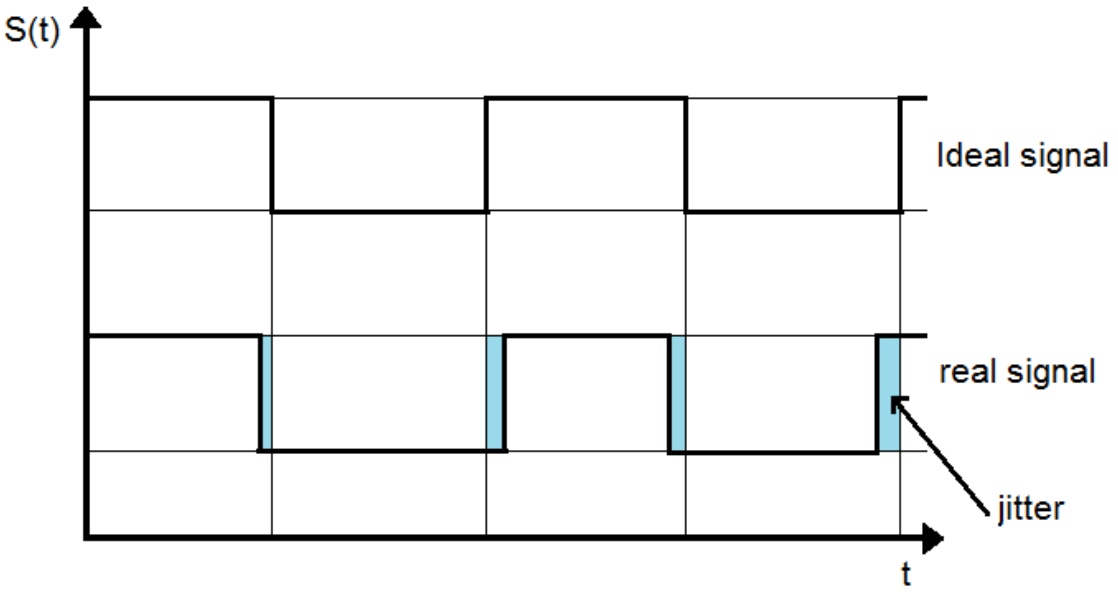

Figure 1.6: Jitter example

Allen deviation:

Another sensitive information for small term stability is the Allen deviation[1], it describes short term frequency stability, and also used as an estimator to estimate the frequency uncertainty in long term, it is basically a deviation or difference of the frequency between two samples, this function depends on the time period of the taken samples, let us take the fractional frequency value $y(i)$ measured at time $t_0 + i\tau$, and $y(i+1)$ at $t_0 + (i+1)\tau$, Allen Deviation is expressed mathematically as 1.4.

$$\sigma_y(\tau) = \left(\frac{1}{2M} \sum_{i=0}^{M-1} (y(i+1) - y(i))^2 \right)^{1/2} \tag{1.4}$$

Or in other words, the Allan Deviation is the variance of M pairs of frequency measurements taken at times t, and $t + \tau$, respectively.

1.4 GPSDO accuracy and Performances

The performance of GPSDO's can vary according to the conception and the components used, even if they are in the same environment they can differ, when the GPSDO is locked to the satellite signals after days or more it should inherent its accuracy and stability form.

The GPS satellite clocks are continuously steered to agree with Coordinated Universal Time , the accuracy they reach are around 10^{-13} per second.

Frequency accuracy over one day is the most important specification to calibration laboratories, because most of the calibrations processes take 1 day or less, so evaluating the frequency accuracy of a GPSDO takes at least one day of averaging. The required accuracy for calibration should be less than 10^{-12} . GPSDO can achieve this accuracy once it is totally locked.

NIST (National Institute of Standards and Technology) estimated the frequency stability of seven different GPSDOs, some of them contain a rubidium oscillators as a local oscillators and the others a quartz oscillators; as shown in the figure 1.7.

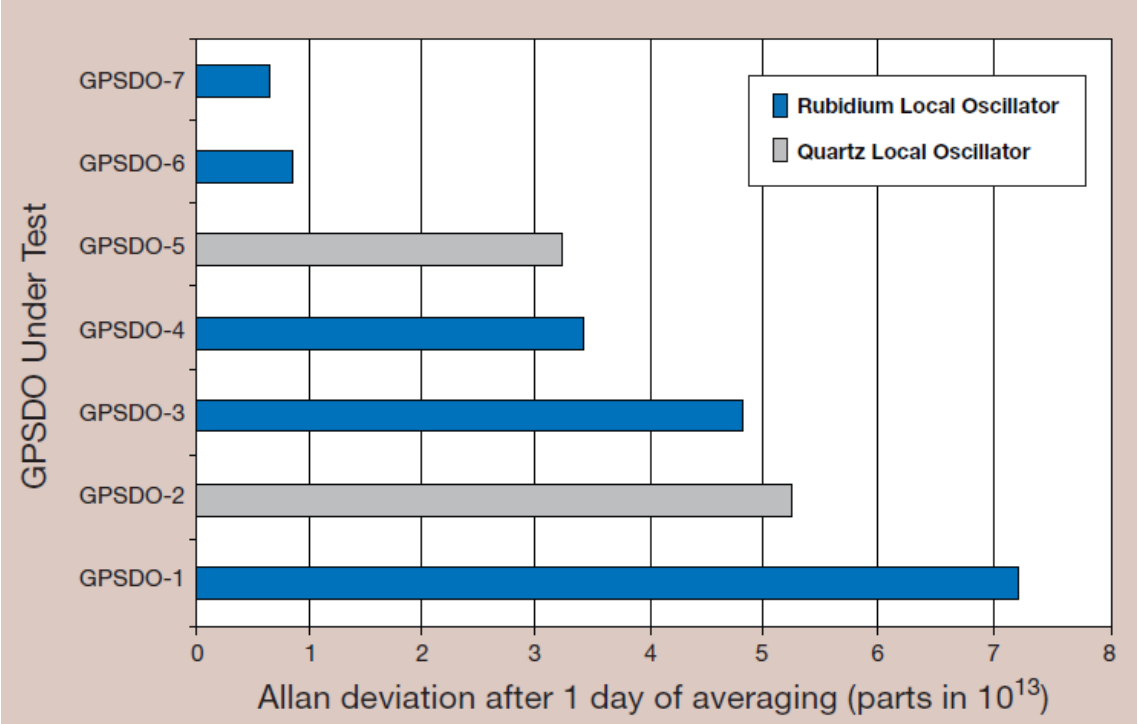

Figure 1.7: Allan deviation of several GPSDOs[1]

This results show that GPSDOs stability can be less than 8.10^{-13} for one day averaging, these are considered as perfect frequency standards for calibration laboratories.

Now the question what is the best choice for a calibration laboratory when it comes to buy a frequency standard, rubidium oscillator, a cesium oscillator or a GPSDO ?

Table 1.1 shows a comparison of the 3 standards.

Oscillator Type	Rubidium	Cesium	GPSDO
Frequency offset with respect to UTC(NIST) (1 day average)	5×10^{-9} to 5×10^{-12}	1×10^{-12} to 5×10^{-14}	1×10^{-12} to 5×10^{-14}
Stability at 1 day	5×10^{-12}	8×10^{-14} to 2×10^{-14}	8×10^{-13} to 5×10^{-14}
Phase noise (dbc/Hz, 10 Hz from carrier)	-90 to -130	-130 to -136	-90 to -140
Life expectancy	> 15 years	5 to 20 years; 10 years is typical	> 15 years
Cost (USD)	$2,000 to $10,000	$30,000 to $75,000	< 15,000

Table 1.1: Comparison between rubidium oscillator, cesium oscillator and GPSDO[1].

There are some other radio systems used as a primary clock, which are less accurate than GPSDO. Many companies, institutes and most calibration laboratories now use GPSDOs as their primary standard. The performances and low cost of the GPSDO make it the best choice, other advantages can also be mentioned such as:

- No need for a periodic adjustment since it steered by GPS satellites continuously.
- It has access to GPS satellites all over the globe, so its placement does not matter unlike the time standards based on radio systems.

After exploring the advantages of using GPSDO as a primary standard let us see now some of its disadvantages, and why the other minority of laboratories do not use it:

- The GPS signals are the first reference for the GPSDO , so it can easily fail when the GPS signal is unavailable, interfered with other radio frequencies or being jammed.
- Also using a GPS antenna is necessary in most cases.

1.5 Conclusion

To conclude, because the GPSDOs are continuously steered to agree with UTC, they will have better long-term accuracy and stability than any free running oscillator, the cesium oscillators included, that is why they are accepted by most calibration laboratories as primary standards.

Chapter 2

Theory and Design of GPSDO

2.1 Introduction

The beginning of this chapter consist in giving a clear explanation about how the GPSDO works, and how it converts the signals coming from the GPS satellites to a frequency reference.

In the next section we talk about the GPS receiver, we discuss briefly about its internal architecture, and how it treats the GPS signals and converts them into data.

The last section is about GPSDO's components design, we go through each block and give its features, and then we conclude by giving the remarks on the performances that we can reach.

2.2 The architecture of the GPSDO

Since our circuit is a PLL based circuit, we need to introduce the basics of a PLL functioning[1].

2.2.1 Universal PLLs diagram

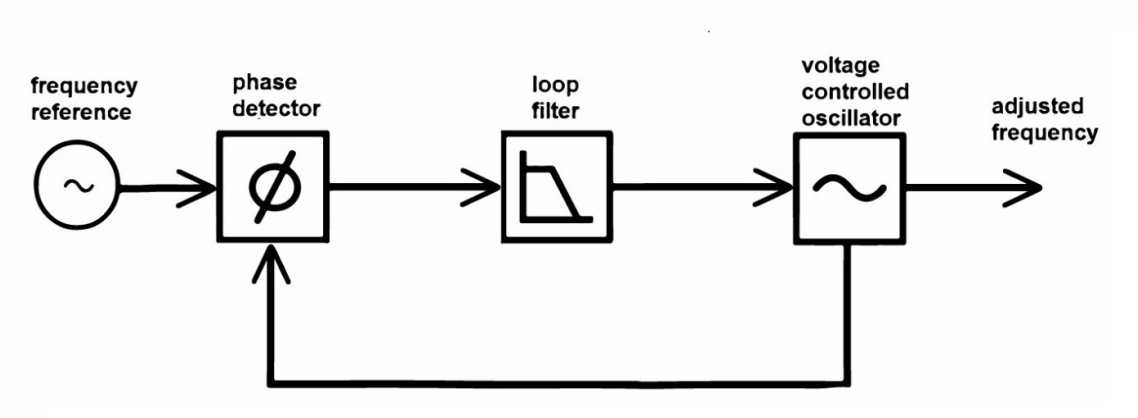

Figure 2.1: Phase locked loop diagram

PLLs are basicaly circuits that allow you to lock two signals together in frequency and phase ideally (figure 2.1). Phase detector whose job is to compare the phases of two AC signals that appear at the input, and then gives you as an output a pulse repitition with a duty cycle propotional to the phase difference of the two inputs. Those pulses go into a low-pass filter to generate a near DC voltage propotional to the phase difference, which is used to adjust the input of the VCO. And once the phase difference becomes stable, the two signals, at the input of the phase detector, will have the exact same frequency[8].

2.2.2 Block diagram of the GPSDO

Now that we have settled the foundation of our circuit let us introduce to you our diagram (Figure 2.2) and give you a rough description as a beginning.

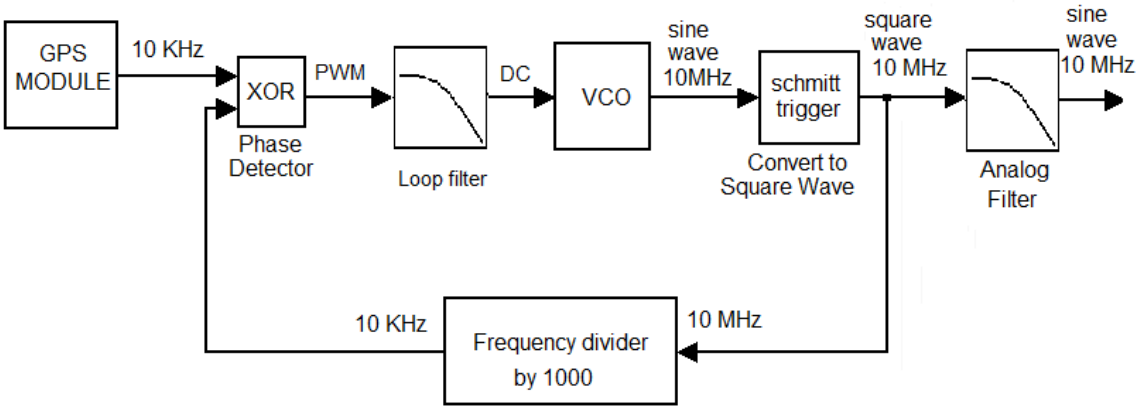

Figure 2.2: block diagram of the GPSDO

The first stage of our PLL is the GPS receiver (GPS module + GPS antenna), at this point we are interested to produce a reference frequency signal, in order to do that the GPS receiver need to know its position and then adjust its own clock according to the GPS satellites; this is done thanks to a very concise algorithm implemented in the GPS and incoming data from several GPS satellites (more than 3). Once the receiver is locked to the GPS satellites we can then extract our reference frequency (10khz in our case).

Now that we have the reference frequency we will put it aside (we will get back to it later), the frequency we wish to adjust is the one coming out of the VCO. The VCO after reaching its operating region outputs a 10MHz sine wave, which will be converted into a 10KHz square wave by the Schmitt trigger, followed by the frequency divider, and then this very signal will be compared to the reference frequency mentioned above.

The phase detector is the one in charge of comparing the phases of these two signals and it generates PWM with duty cycle proportional to phase difference, PWM will then be averaged to a near DC voltage by the loop filter, and after that, it feeds the VCO in order to adjust its frequency. The process repeats itself continuously until the PLL locks the two signal's phases.

The analog filter converts the square wave signal into a sine wave, the signal that we use.

2.3 GPS receiver data acquisition

Most users think of GPS as a means of determining position, but the constellation of 31 satellites is also an excellent time keeper. Each satellite contains two rubidium and two cesium atomic clocks[2]. These are monitored against atomic clocks on the ground, and the whole system is continuously calibrated against the world wide time standard, Universal coordinated time (UTC).

The GPS receivers improved drastically in the last 20 years, they improved so much so that it became very easy to buy one, and using GPS receiver for determining time became very common nowadays.

In this section, we discuss the GPS receiver (module +antenna), how it acquires data in general, and more specifically we discuss the one we used.

2.3.1 GPS Satellite overview

Each GPS satellite transmits data on two primary channels:

L1: $f_1 = 1,575.25MHz$

L2: $f_2 = 1,227.60MHz$

It has on board 4 atomic clocks, two rubidium clocks and two cesium clocks, they determine a fundamental frequency $f_0 = 10.23MHz$, from which frequency carriers are extracted[11,12].

The data sent through these channel are essentially 25 frames (we will not go into details), and the information within are:

- The PRN (pseudorandom noise): tells us which satellite is sending data.
- Satellite ephemerides: gives the position and velocity of the satellite.
- Ionospheric modeling coefficients: the ionosphere introduce errors and in order to correct them coefficients are sent.
- System time: gives precisely the time of day.
- Clock corrections: corrections added to the system time for a more accurate time.

2.3.2 GPS+GSM Combination Antenna JCB009

Is an antenna that receives GPS signals and GSM signals at the same time, though we will use only the GPS antenna (figure 2.3) that acquires the electromagnetic signals from the different GPS satellites at 1,575.25 MHz, it has the following features:

- Center Frequency: $1575.42 \pm 1MHz$.
- Band Width : $CF \pm 5MHz$.
- LNA Gain : $28 \pm 2dBi$.
- SMA male connector.

Figure 2.3: GPS+GSM Combination Antenna JCB009

2.3.3 GPS module: TU30-D140

In order to introduce the module properly, let us first see how a GPS receiver generally works(Figure 2.4):

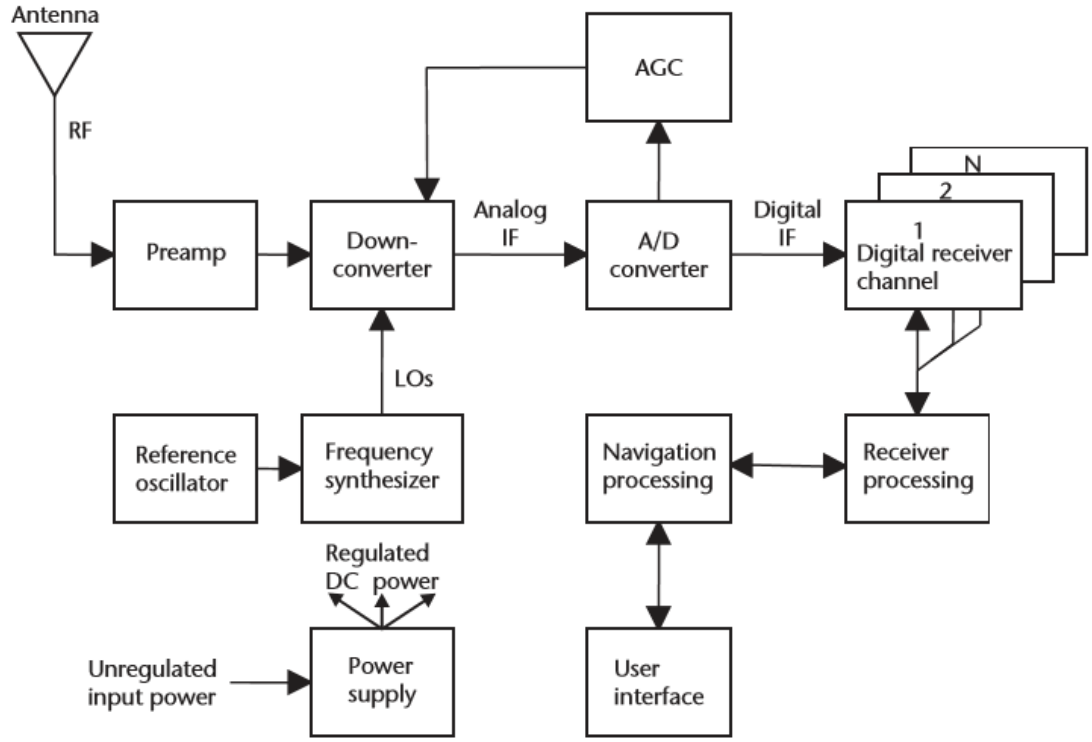

Figure 2.4: GPS receiver diagram[2]

First the signal comes from the antenna at a frequency of $1.5GHz$ (L1 band) then it gets amplified and filtered, after that it passes through the mixer to be down-converted to an intermediate frequency, and then it gets demodulated to a base-band signal provided a

LO from the frequency synthesizer, and finally converted to a digital signal.

The signal once ready enters the digital receiver channels according to GPS satellites from where the signals comes, and then the receiver processes the data to be ready for the user.

2.3.4 Diagram of the TU30 GPS receiver

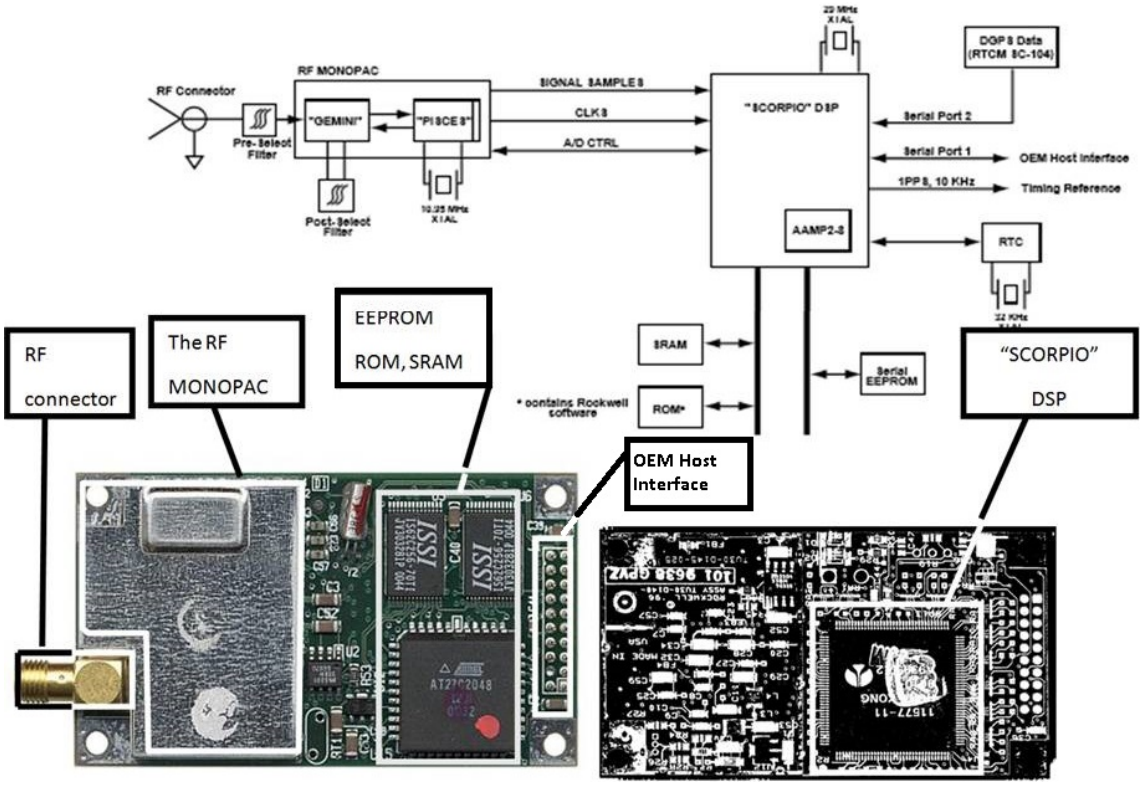

Figure 2.5: diagram of the TU30 GPS receiver

The RF connector

The RF connector is a 50 Ohm standard, SMB plug.

The RF MONOPAC

It is a bloc where the signal is being transformed from an RF analog signal to a base-band digital signal, the bloc contains the pre-amplifier, the filter, the mixer, the A/D converter and the frequency synthesizer.

SCORPIO DSP

It is the processor unit that handles all the computation regarding the position and the time adjustment.

The technique used to determine the position of the GPS receiver is called the trilateration problem (figure 2.6), it estimates the location of the receiver given the position of the satellites, it uses an algorithm within the processor unit for the computation.

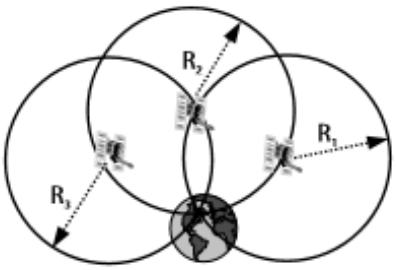

Figure 2.6: Trilateration technique

Then once the location is determined (with an uncertainty due to the GPS receiver clock errors) the DSP includes the data coming from the other satellites, and through a second algorithm of estimation the clock of the GPS receiver gets readjusted to a more accurate one.

EEPROM, SRAM, ROM

The memory blocs are in charge of booting the program of the GPS receiver in the case of the ROM, while the SRAM handles the intermediate computation for the DSP and the EEPROM loads the previous data from the last position of the receiver.

OEM host interface

The OEM host interface consists of several pins each of which interacts with the GPS receiver in a certain way, as shown in the Appendix B.

The pins of interest are the 10KHz clock output and the serial data output, respectively on pin 11 and pin 20, so 10 KHz signal is the reference frequency that adjusts our VCO, while serial data output is the port from which we can see the position and the time reference according to the GPS satellites, and most importantly we can check if the GPS is providing valid data.

In order to get the data we want from the GPS receiver through the SDO we should be able to understand the protocol it is using, they are two possible message format protocols;

the NMEA protocol and the binary protocol, there are chosen according to table in the Appendix C .

NMEA protocol

The protocol we use for our circuit is the NMEA protocol, so let us see how it works:
The basis of the NMEA protocol is the RS232 communication protocol that relies on sending one character (ascii code) at a time, the format follows the Figure 2.7[9].

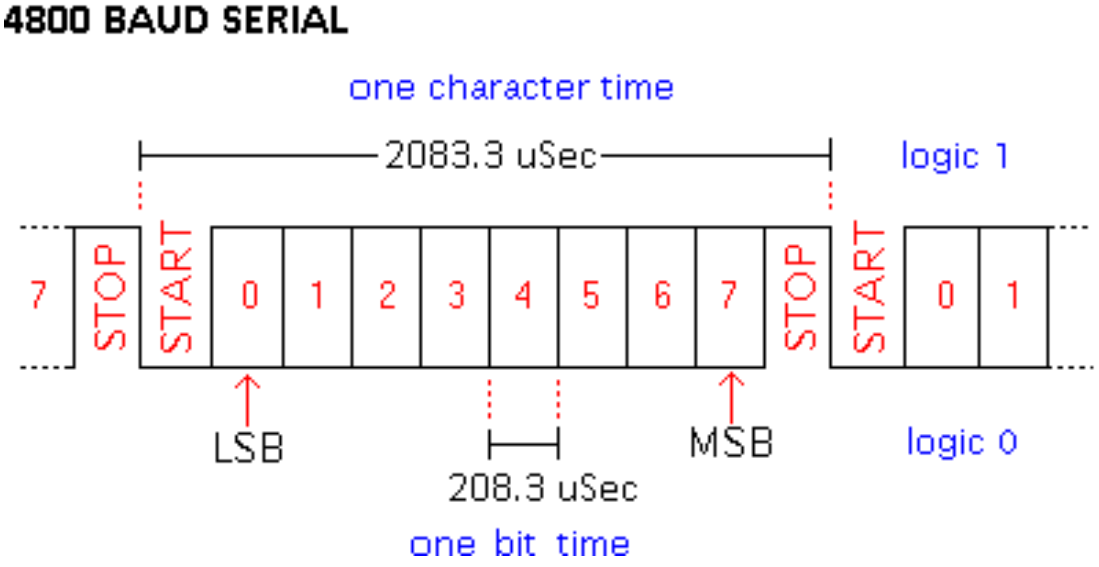

Figure 2.7: NMEA protocol

The maximum total number of characters in any sentence is 82; that is, a maximum of 79 characters between the starting delimiter "$" and the terminating <CR><LF>.
A number of these sentences are dedicated to GPS and GLONASS systems, while the remaining sentences support other devices such as echo sounders, gyros, and others. Our discussion is restricted to one sentence only, the GPRMC (Differential Global Positioning Recommended Minimum sentence C).

RMC - NMEA has its own version of essential GPS pvt (position, velocity, time) data. It is called RMC, The Recommended Minimum data for GPS, which looks similar to:[10]

$$\$GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230394,003.1,W*6A$$

Where:

RMC Recommended Minimum sentence C
123519 Fix taken at 12:35:19 UTC
A Status A=active or V=Void.
4807.038,N Latitude 48 deg 07.038' N
01131.000,E Longitude 11 deg 31.000' E

022.4	Speed over the ground in knots
084.4	Track angle in degrees True
230394	Date - 23rd of March 1994
003.1,W	Magnetic Variation
*6A	the checksum data, always begins with *

2.3.5 Display led for indicating valid data

In order to check if the GPS is connected to at least 4 satellites (so that the frequency reference is guaranteed to be very accurate). We need then to check if the GPS is providing valid data from the NMEA frame, to do so we used a microcontroller PIC12f629 and a green led as an indication for the GPS valid fix data.

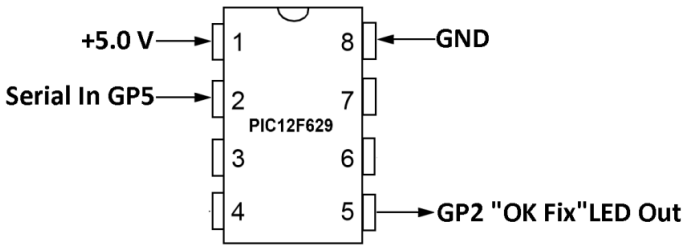

Figure 2.8: used pins of the microcontroller

The first step in our program is to check the first character of the frame which should be $, then we check for the frame type (GPRMC, GGA etc..), after we made sure to be in the right frame we look for the 14th character which should present an ”A” for valid data or not otherwise.

Figure 2.8 shows the pins to implement this operation.

2.4 Voltage controlled oscillator

We discussed in the last section how the GPS satellite transmits a very accurate clock to the receiver, and therefore how this frequency is obtained, so no that we have our reference frequency, we choose our VCO to complete with.

The VCO (voltage controlled oscillator), as its name refers to, is an oscillator that generates a signal whose frequency is tunable with an external voltage, the VCO is the main device in our system, there are many types and technologies and it has many applications like PLLs, frequency synthesizer and FM modulation .

To choose the suitable VCO we need to select the necessary preferences:

First one is the oscillator centre frequency, and the one we need is the 10 MHz.

Second one is the frequency range, actually this parameter is very important in our application because we are using a single frequency so we need a narrow band VCO, The other ones are the stability, accuracy, and its immunity to the external factors like temperature, humidity, electromagnetic noise, mechanical vibrations and shocks.

2.4.1 Choosing the controlled oscillators

The type of oscillators we will use is of LC resonators types based on crystal oscillator ,LC resonators can be tunable over a narrow range of frequency, their stability is less than 10^{-5}, the crystal oscillators are more stable if we take into account the external factors especially the temperature, that why there are types called TCXO and OCXO (temperature/oven control crystal oscillator) [5]:

TCXO: temperature compensated crystal oscillator, as the name suggests, takes into account any deviation of the frequency due to the external temperature and corrects it either analogically or numerically, there is also what we call DTCXO, this technology is used for stability higher from 10^{-6} to 10^{-7}.

OCXO: means Oven Controlled Crystal Oscillator, oscillator circuits and crystal are isolated and surrounded by metal case called oven, the oven will heats the circuit to the proper temperature and stabilizes it in order to prevent changes in the frequency due to variations in ambient temperature, this oscillator has the highest frequency stability possible with a quartz varies from 10^{-8} to10^{-9} and they cost from 100 dollars to 1000 dollars for a better qualities ,and they are typically used in radio transmitter, professional communications equipments, and widely used for precision frequency measurement.

For more stability we switch to the atomic clocks (rubidium and cesium), which are very expensive and much more precise. After this small comparison of the performances and prices we find that selecting the OCXO type for our project is the best option, the one we will use is a 10 Mhz OCXO from HP company referenced by $10811B$ (figure 2.9), This device provides very suitable and powerful performances for our project, which is explored in the next part.

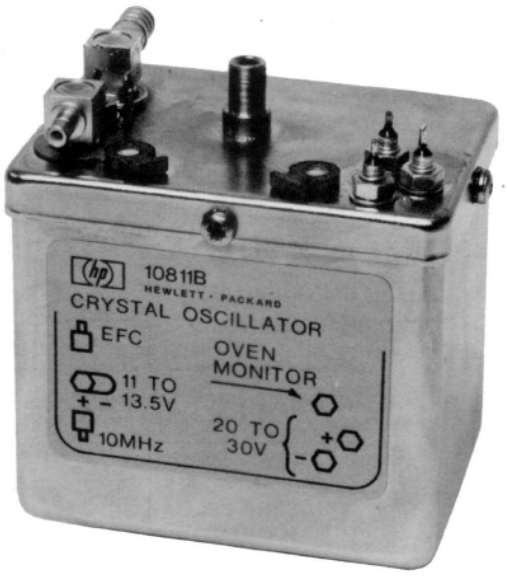

Figure 2.9: Image of 10811B VCO.

Frequency stability

Stability in long term smaller than 1.10^{-7} for continuous operation for one year without correction or 5.10^{-10} per day, it means if we use this device as a clock it does not cause drifts grater than $50ns$ a day.

The VCO's data-sheet shows a table of different values of its phase noise (Table 2.1).

Offset from Signal f [Hz]	Phase Noise Ratio $\mathcal{L}(f)$ [dBc]
10^0	-90
10^1	-120
10^2	-140
10^3	-157
10^4	-160

Table 2.1: phase noise values of the VCO.

Data-sheet provides also the Allan deviation for different values of averaging times (τ) (Table 2.2).

Averaging Time τ |seconds|	Stability $\sigma_y(\tau)$
10^{-3}	1.5×10^{-10}
10^{-2}	1.5×10^{-11}
10^{-1}	5×10^{-12}
10^{0}	5×10^{-12}
10^{1}	5×10^{-12}
10^{2}	1×10^{-11}

Table 2.2: the stability of the VCO.

For example we take $\tau = 1s$, the Allen deviation is only 5.10^{-12}, it means the frequency drift is of $5\mu hz$, it may appear between 2 simples taken in t_0 and $t_0 + 1$ s due to internal noise, compared to the other oscillators this one is showing a great stability in a short term.

Electrical Frequency Control (EFC)

The voltage control input can go from -5v to +5v sweep 1Hz as total, it means if VCO is configured to generate exactly 10^6 Hz at EFC= 0v the voltage control can change this frequency from 999999.5 to 10000000.5 Hz which is assumed as a very narrow range , With this values we calculate the sensitivity of this device (K_{vco}) , $K_{vco} = \dfrac{\Delta f}{\Delta V} = 1/10 = 0.1hz/v$ And the generated signal is a sine wave of 0.55 ± 0.05 Vrms into a 50 ohm load and 1 Vrms $\pm 20\%$ into 1K ohm load.

Theory of operation

Many circuits and topologies exist for OCXOs, in this part we go more deeply through some of the basics of this device specifically and how it works, and because it is based on the crystal oscillator, it is more convenient if we start by exploring this component.

Crystal oscillator (or quartz) is used in many application to produce a specific frequency, due to its simplicity and stability, it is all about a piezoelectric which converts the mechanical vibration to a voltage vibration and vice versa. Mechanical vibration is generated by applying a voltage across this material , and returning to its previous position generates a voltage which will be fed back again , and the resonant frequency depends on the size and the shape of this piezoelectric, its behavior is similar to RLC circuit, so it is modeled by the schematic shown in Figure 2.10 [11] .

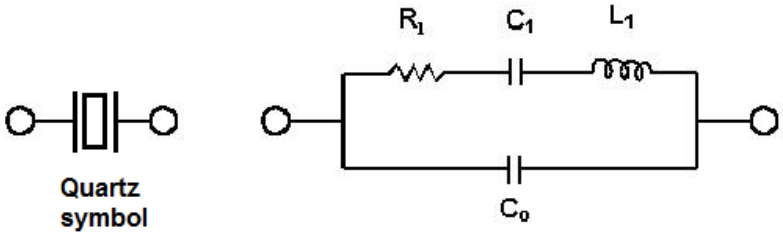

Figure 2.10: Quartz model

C_1 L_1 R_1 , are called emotional parameters, in other words l_1 represents mechanical mass of the quartz, C_1 is the mechanical springiness of the crystal as it vibrates, R_1 represents the energy losses and C_0 is the capacitance of the electrodes placed across the crystal which is the only actual component and it provides a very low value, but the rest are only emotional parameters and mechanical counterparts.

The inductance L_1 and the capacitance C_1 are in series with each other which means that there is going to be a frequency, at which the two reactances will be equal in opposite signs and cancel each other ,this frequency called the resonant frequency of the crystal, we use quartz circuit because the Q factor is very sharp.

Generally any oscillator can be seen as 2 main parts, amplifier and a feedback network which feeds the amplifier network back to its input as the figure 2.11 shows.

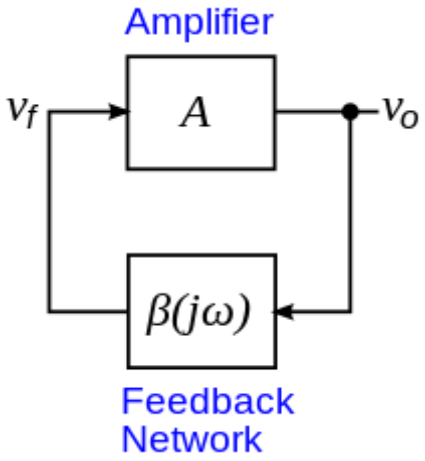

Figure 2.11: Block diagram of the oscillator

The feedback network is usually designed to only feedback signals at a particular frequency because we want it to oscillate, and the basic criterion is known as Barkhausen condition, and it states that the total loop gain or in other words the gain of the amplifier times the gain of the feedback network has to be equal to one at the stability point of

operation, it means the fed signal should be amplified not attenuated , and the other criterion is that the total phase shift has to be zero, in other words the feedback signal must be in phase with the original signal that appeared at the input, any type of oscillator is based on this theory, for example, Pierce Crystal Oscillator which is widely used in many applications, but we only focus on the Colpitts-type crystal oscillator which is the main circuit of our VCO.

Colpitts crystal oscillator: this type is no exception to the Barkhausen criterion, though there is another secondary rule that characterizes it as a colpitts oscillator, which consists in that the gain of the feedback network, it has to be pure real value in other words, the input and the output signals have the same phase. Feedback circuit (resonant circuit) is modeled by the schematic in figure 2.12 [11].

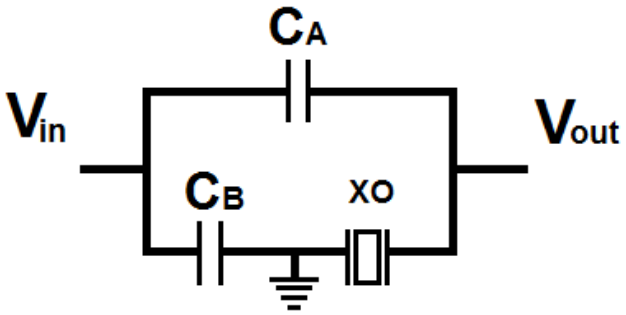

Figure 2.12: Resonant circuit

At the resonant point the crystal is primarily inductive, so indeed we have a very high Q inductor connected across two capacitors, which means the inductance and the two capacitors will resonates at certain frequency, to give a better idea about this frequency, let us model the crystal oscillator as an inductance in series with a resistance , which gives a total impedance of $jX_L + R_e$ with $X_L > 0$, the circuit will resonate at $X_e = X_{C_A} + X_{C_B}$, where X_{C_A} and X_{C_B} are the impedances of C_A and C_B respectively (Figure 2.12) .
Resistance R_e is relatively small, so if we calculate the gain of the network B, it gives the formula 2.1.

$$\frac{V_{out}}{V_{in}} = \frac{R_e + jX_e}{R_e + jX_e - jX_{C_B}} \approx \frac{X_{C_A} + X_{C_B}}{X_{C_A}} \tag{2.1}$$

Next question is how to control the frequency with a dc reference voltage (EFC) , As we can notice, changing one of the capacitors leads to an inversely proportional deviation of the resonant frequency of the feedback network, which is the oscillation frequency, in this case a variable capacitance diode (varicap) is used as the schematic shows (Figure 2.13).

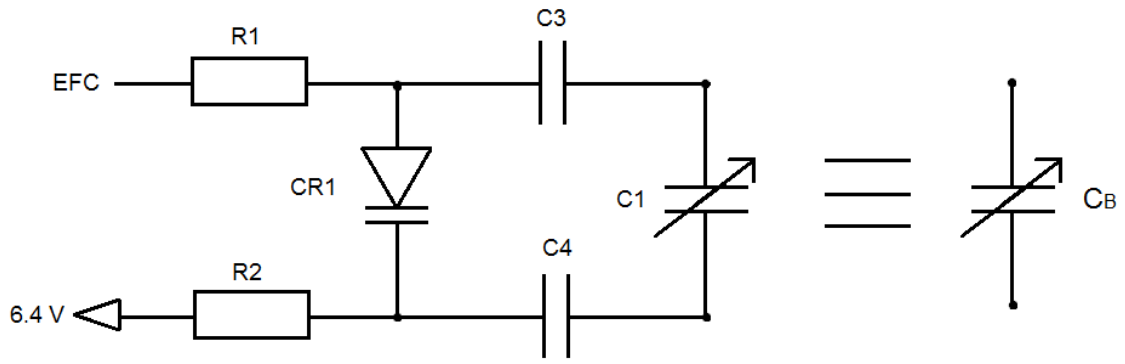

Figure 2.13: Resonant circuit with varicap.

The $R1$ and $R2$ used as a current limitation and the capacitors $C3$ and $C4$ are used as a DC blocking capacitors with relatively large values , variable capacitor $C1$ is adjustable from outside, to adjust the frequency before using this device, the varactor ($CR1$) is added in parallel with the DC voltage control (EFC), its capacitance depends on the DC voltage applied to it (reverse bias),the circuit is designed to allow the control voltage to go from -5 volts to $+5$ volts, giving a tuning range frequency of $\approx 1Hz$, which decreases with the augmentation of EFC (Electrical frequency control).

Oven heater

The purpose of the oven is to shield the oscillator crystal and electronics from normal ambient temperature changes, we mentioned before the temperature variations has a big effect on the crystal oscillator, to maintain a constant oven temperature, which is higher than the highest expected external temperature ,the VCO provides a temperature controller whose job is to turn on the heater, when the measured temperature by the thermostat is lower than $80°C$, and switch it off when it reaches $84°C$.

Calibration and tests

This device provides an oscillator frequency adjustment to calibrate the offset frequency before using it so the steps we followed during the calibration are mentioned below:

1) Connecting the VCO to a precise oscilloscope, synchronized by an external reference source for a better precision (in our case we used a professional GPSDO as an external reference).

2) Setting the sweep speed to $0.01\mu s/div$, we should see the displayed chart moving .

3) Using isolated tool we adjusted the oscillator for a minimum sideways movement , the Coarse Frequency Range is 10 Hz with 18 turn.

After manually adjusting the frequency offset, we calculate the frequency offset error, we do that by measuring the speed of the chart in the oscilloscope, we find it less than $20s/div$, it means it takes $t = 20s$ to drift for $\Delta t = 0.01\mu s$, and that gives the result shown in 2.2 .

$$\Delta f = f \times \frac{\Delta t}{t} = 10Mhz \times (0.01\mu s)/(20s) = 5mHz \tag{2.2}$$

Where Δf is the frequency offset error, and f is the frequency of the signal.

And that should be enough, because the frequency offset error is covered by the control voltage, which has a range of $1Hz$ as we mentioned above.

2.5 Schmitt trigger

Output of the VCO is a sine wave ,according to its data-sheet, the output voltage is $1Vrms$ into $1K\Omega$ load, which means the voltage from peak to peak is $V_{p-p} \approx 2.8V$ with a zero offset, though the frequency divider and the phase detector accept only a square wave from 0V to certain positive voltage as an input, so the task here is to convert this sine wave of 1.4V amplitude and a 0V offset to a square wave from 0 to 5V.

The solution is to use a DC coupler circuit to change the offset of that signal to 2.5V and comparator to transform it to the desired form as the Figure 2.14 shows :

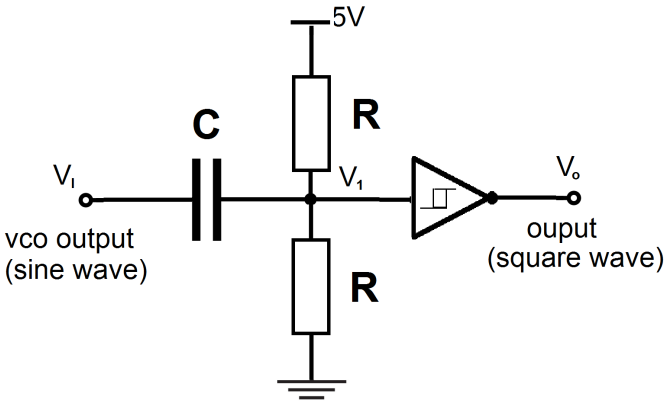

Figure 2.14: Comparator circuit

In the dynamic mode the cutoff frequency of that circuit is shown in 2.3 [11].

$$f_c = \frac{1}{2\pi\frac{RC}{2}} \tag{2.3}$$

And the $10Mhz$ input signal should not be filtered , this condition allows us to choose the values of R and C for $f_c \gg 10MHz$, by choosing $R = 100K\Omega$ and $C = 10pF$, it gives

$195MHz$ as a cutoff frequency, and that works fine.

The Schmitt trigger we used is HD74HC14T, which can operate at 10Mhz frequency , and has the following characteristics for 4.5V VCC in a typical conditions supply :

- High level input threshold voltage : $V_H = 3.15V$
- Low level input threshold voltage : $V_L = 0.9V$

This values are gathered from the datasheet ,to get the exact ones for $5V$ supply we did some test experiments and we found V_H is around $3.9V$ and V_L around $1.1V$, which should give a perfect square wave if we applied a sine wave in the inputs with an offset of $2.5V$.

2.6 Frequency divider

After converting the sine wave into a square wave, comes the step of compare it against the frequency reference, but before, that we need to divide it by a factor of 1000.

the frequency divider in our study is very important, it is the item that will transform a $10MHz$ signal into a $10KHz$ signal, so that we compare it against the reference frequency , the first idea was to use 2 Dual decade ripple counter 74HC390N, this chip can provide frequency division of 2,4,10,20,50 or 100 that means using 2 of them should be enough to create a 1000 counter,but as a better solution we found that using a programmed microcontroller 12F629 can provide the same results with less cost, less power consumption and less circuit complexity.

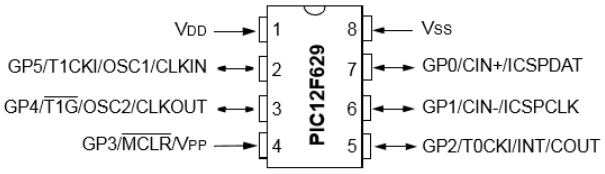

Figure 2.15: PIC12F629 pins[3].

The way to take advantage of the PIC12F629 is through the features it offers. Beginning with CLKIN Figure 2.15(clock input).

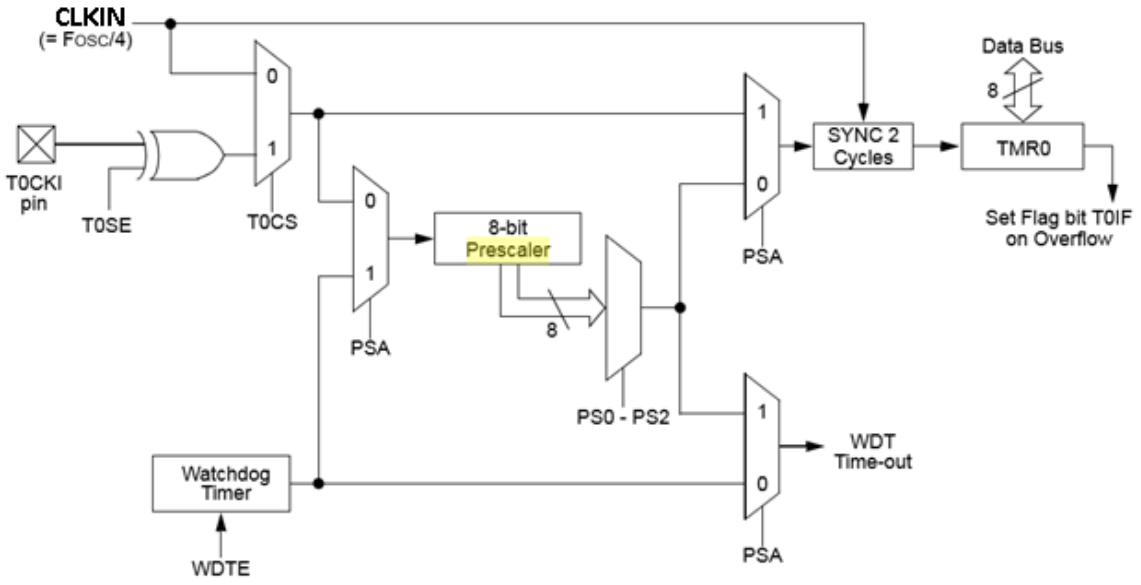

Figure 2.16: prescaler diagram for the divider

The circuit above shows how the TMR0 gets incremented, also, we notice that the signals entering different blocks can be modified in the software, and the counter TMR0 is being synchronized by the CLKIN each period.

Explanation of the code

The GPIO0 is the pin on which we make changes to refer to our divided frequency, there is a routine that takes place in the code, it repeats itself every 125 cycles, which represents half of the period, which means 250 cycles for a whole period, adding to that the fact that $Fosc/4$ equal an instruction frequency, we get $250 \times 4 = 1000$ clock cycles.

2.7 The phase detector

There are multiples techniques to realize the phase detector, In this project we chose to use a digital logic XOR gate, due to its function which gives low when the two inputs are the same (which means both are true or both are false) and one (or high) if the two inputs are different[11].

The first input comes from the GPS module, and the other one comes from the frequency divider, these 2 signals have a frequency of 10 KHz , so the resulted signal of the phase detector is a 20 KHz PWM (phase modulation signal), with a duty cycle depends on the phase difference of the 2 signals like the figure 2.17 shows.

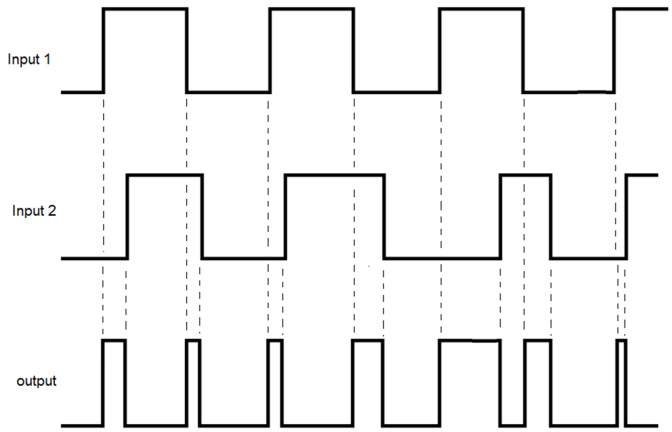

Figure 2.17: the phase detector reaction

The component used in this project is 74VHC4046, which will be more detailed in the next lines[12]: this integrated circuit provide XOR gate as a phase detector , according to the datasheet, it works with a supply voltage from 2 to 6v , and an output current that can reach 25 mA , and that should be enough for our application.

Figure 2.18 shows the block diagram of this circuit.

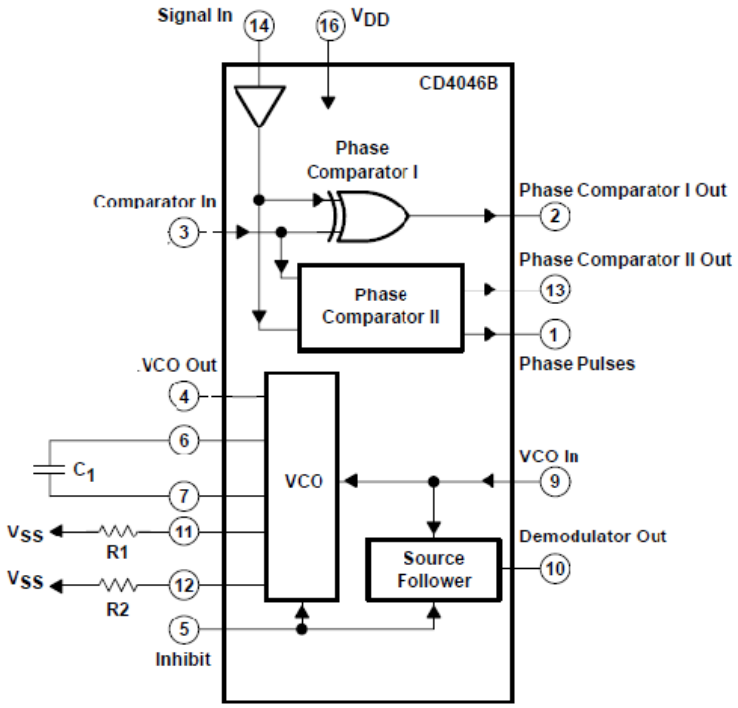

Figure 2.18: the block diagram of 74VHC4046

In our case, we use only the phase detector which is label by phase comparator1 in the block diagram, so the pins used are pin 14 and pin 3 , as the two inputs for the 2 signals and pin 2 the output.

We can see this circuit as PWM generator of 5 v amplitude, and duty cycle proportional to the phase difference as the chart in figure 2.19 .

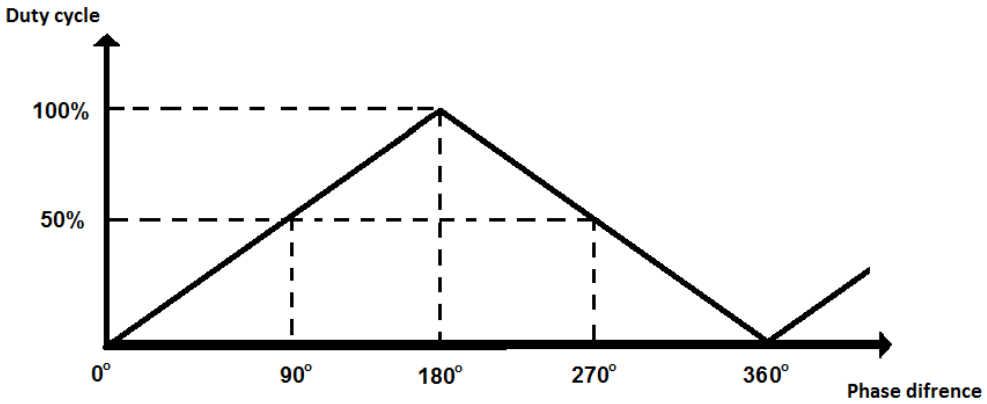

Figure 2.19: The output of the phase detector according to the phase difference

In the VCO part we mentioned that the reference frequency is calibrated at $2.5V$ in the reference input (EFC) of the VCO so to obtain that voltage level, the duty cycle must be around 50% , which conditions the phase difference to be 90° when the PLL is locked. And finally to convert this information of the duty cycle to a DC voltage, we use a filter which will be more explored in the next lines.

2.8 Loop filter

Is a low-pass filter, it filters the output of the phase detector and produces steady DC voltage, so its job is to smooth the input signal (PWM output), and converts it to a near DC voltage whose amplitude is proportional to the duty cycle of PWM signal, which is in theory the average of that input signal calculated as 2.4.

$$V_{out} = \frac{V_{max} \times T_{on}}{T} \tag{2.4}$$

where :
V_{out} the output signal.
V_{max} the maximum value of the input PWM signal which is $5V$ in our case.
T_{on}/T is its duty cycle.

The most simple design for that filter is RC filter, which is used in our project,though there is a diversity of loop filters, which depend on the application, like in some applications where the VCO needs more power in its input, an active filter is necessary, but in our project the amplifier may add some noise to the PLL.

Recently the charge pump became widely used due to its performance in some PLL applications, charge pump is a technique that consists in converting the voltage form to current form, than it is followed by a loop filter, which gives minimum noise[13].

There are different topologies of RC filters used, like the one shown in the (figure 2.20), this one is commonly used to increase the locking speed which is a very sensitive criterion for some PLLs like FM demodulators.

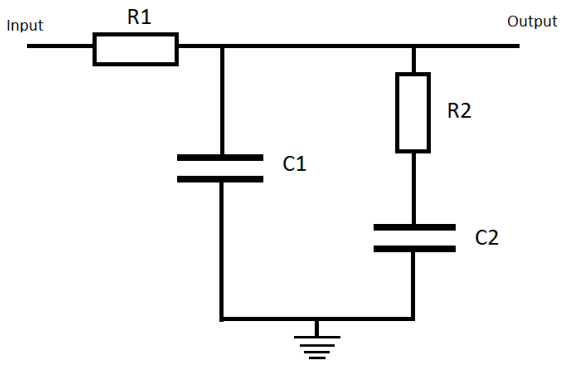

Figure 2.20: third order loop filter

And finally for digital PLLs the loop filter is only a program.

2.8.1 Loop filter design

The techniques used for loop filter designing varies from an application to another, and it depends on the required specifications, the next lines shows the most basic specifications for loop filter design [11]:

- Bandwidth: generally the standard PLLs frequency reference are narrow banded as in our project, although some other applications requires wide band PLL.
- Time to lock: this criterion determines how fast the PLLs locks to the reference frequency, this requires some extra math and theory for a better time response, but for narrow band PLLs this criterion is not important.
- Noise : not only the noise produced by the loop filter, but also the residual ripples which comes from rectifying the input signal of the filter, it can add some phase, because the output of the filter is attached delicately to the VCO control voltage noise.

- The other components specification: sometimes the loop filters can be different for the same application because of the different components used, for example the range of the control voltage of the VCO, or the input impedance of the VCO, which has a big influence on the cutoff frequency of the filter .
- There are other specifications, that should be respected for other applications, like the external factors and more.

After seeing the different aspects of loop filter design, now the question is which one should be considered for our project? , the first criterion is the operating frequency which is $20khz$, and second one is how smooth the signal should be, the only way to answer this question is to take a look at the VCO datasheet, the manufacture of this device limits the noise level of the control voltage to $100\mu V$, which means the maximum residual ripple level must be less than $100\mu V$, and finally the input resistance of the VCO is $100k\Omega$.

Figure 2.21 shows the loop filter schematic, and how it is connected to the VCO load.

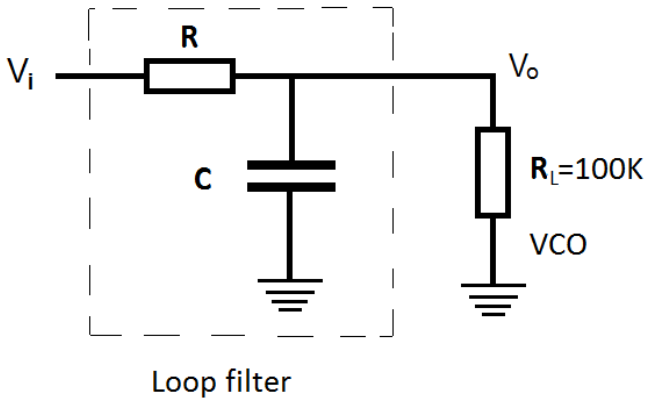

Figure 2.21: loop filter schematic

the next step is to find the best values of the loop filter, which are the resistance R and capacitor C , based on the two criteria as we mentioned above, first the input resistance of the VCO, and second the fluctuation of the output signal V_o should be under $100\mu V$ peak to peak, this fluctuations are known as the residual ripples, which come from charging and discharging the capacitor, it is labeled by V_{p-p}, Figure 2.22 shows the output signal, when the loop is locked, which means its average stays stable .

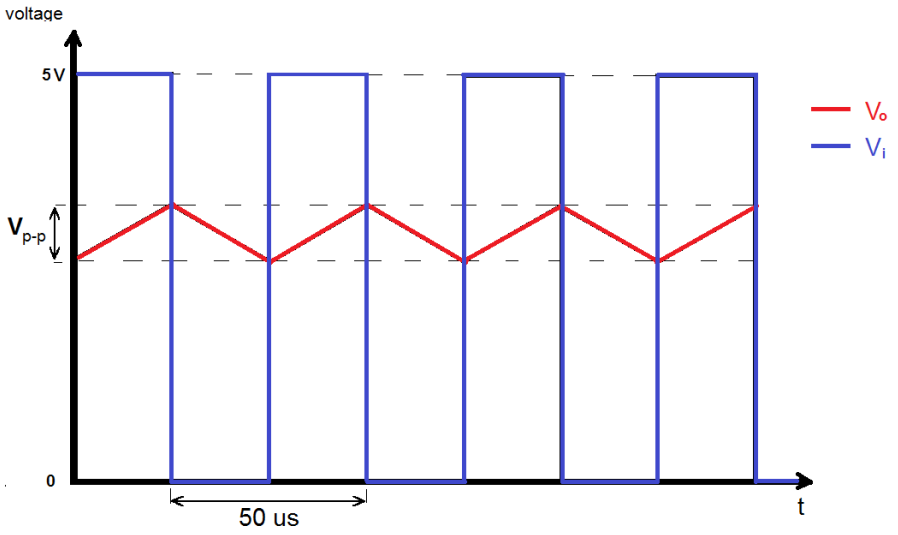

Figure 2.22: Output signal of the loop filter

Where V_i is the PWM signal coming from phase detector, and V_o is the output signal of the loop filter that enters to the VCO, which leads to the equation 2.5 .

$$I_c + \frac{V_0(t)}{R_L} + \frac{V_0(t) - V_i(t)}{R} = 0 \tag{2.5}$$

I_c is the current that flows through the capacitor, and it is equal to : $C\frac{dV_0(t)}{dt}$, which lead to 2.6 .

$$RC\frac{dV_0(t)}{dt} + V_0(t)\left(\frac{R}{R_L} + 1\right) = V_i(t) \tag{2.6}$$

The next step is to solve this equation, the two modes, charging or discharging give the same results approximately, so we choose to solve in the discharging mode when $V_i(t) = 0$.

And because of the short variation of $V_o(t)$ we can assume that this signal is a linear function equal to $V_0 + (\Delta V_0/\Delta T)t$.

With V_o is the average of $V_o(t)$, ΔT is the discharging time or the half period of the input signal, which is equal to $25\mu s$, and the ΔV_o is V_{p-p} as figure 2.22 shows.

And finally this small variation allows us to do the approximation 2.7 .

$$V_0(t) = V_0 + \Delta V_0(t) \approx V_0 \tag{2.7}$$

Where V_0 is a constant that represents the average signal, and it is equal to $2.5V$ in our case, all of these assumptions lead us to the simplified equation 2.8 .

$$RC\frac{\Delta V_0(t)}{\Delta t} + V_0(t)\left(\frac{R}{R_L} + 1\right) = V_i(t) \tag{2.8}$$

By replacing $V_i(t)$ by 0 it gives (2.9)

$$\Delta V_0(t) = -\frac{\Delta T}{RC} + V_0(t)\left(\frac{R}{R_L}+1\right) \tag{2.9}$$

And $|\Delta V_o|$ should be smaller than $\Delta V_{max} = 100\mu V$ and that leads to 2.10 .

$$RC > \frac{\Delta T}{\Delta V_{max}} V_0 \left(\frac{R}{R_L}+1\right) \tag{2.10}$$

Now, we have two variables to find, for the resistance it is better to be big enough to make the capacitor very small compared to R_L to prevent the voltage drop in the VCO input, so it is reasonable to choose it $R = R_L/10 = 100K/10 = 10K\Omega$, and for the capacitor we have 2.11.

$$C > 1.1V_0 \frac{\Delta T}{R\Delta V_{max}} \rightarrow C > 93\mu F \tag{2.11}$$

So we chose a $C = 470\mu F$.

2.9 Analog filter

We take the $10MHz$ output signal from the Schmitt trigger and not from the VCO, for two reasons :

- To avoid any external noise, that might come from the device, which is connected to.
- To isolate the VCO form the external circuits, we let the trigger takes the shock, because it is much cheaper.

This signal is a square wave signal , we can convert it to a sine wave by applying a passive low pass filter (which is located at the output of the PLL as the figure 2.2 shows), if we take a look at the square wave spectrum, it contains multiple of Diracs, the biggest one is located in the main frequency ($10MHz$) and the ones beyond this frequency are located at frequencies $(2n+1) \times 10MHz$, that decay so on and so forth (figure 2.23) :

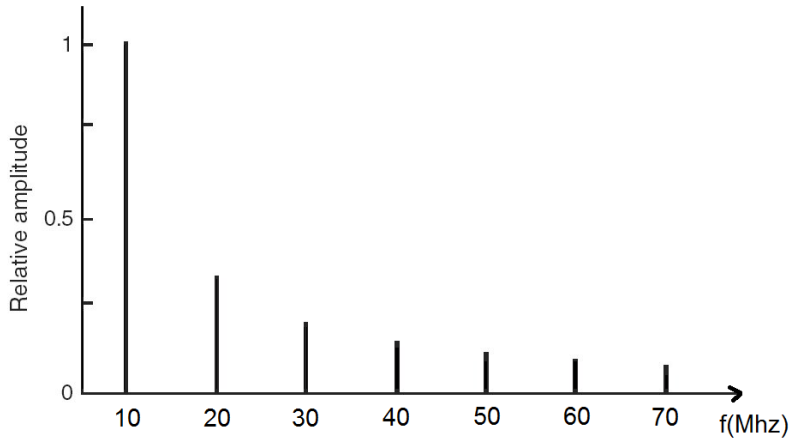

Figure 2.23: square wave spectrum

So the cutoff frequency should be between the $10MHz$ and $30MHz$ to reduce all of the other harmonics , the second harmonic located on $30MHz$ has an amplitude of $-9.5dB$ compared to the main frequency , we minimize the noise in our circuit to prevent any device attached to this frequency reference to be affected, we also should have a table amplitude for professional uses, so it is necessary to choose a sharp low pass filter with minimum ripple at the pass band.

In general, to design a filter, the first step is to specify filter response parameters which consists of the pass-band, stop-band, transition-band and pass-band ripple (filter model) (figure 2.24)[11].

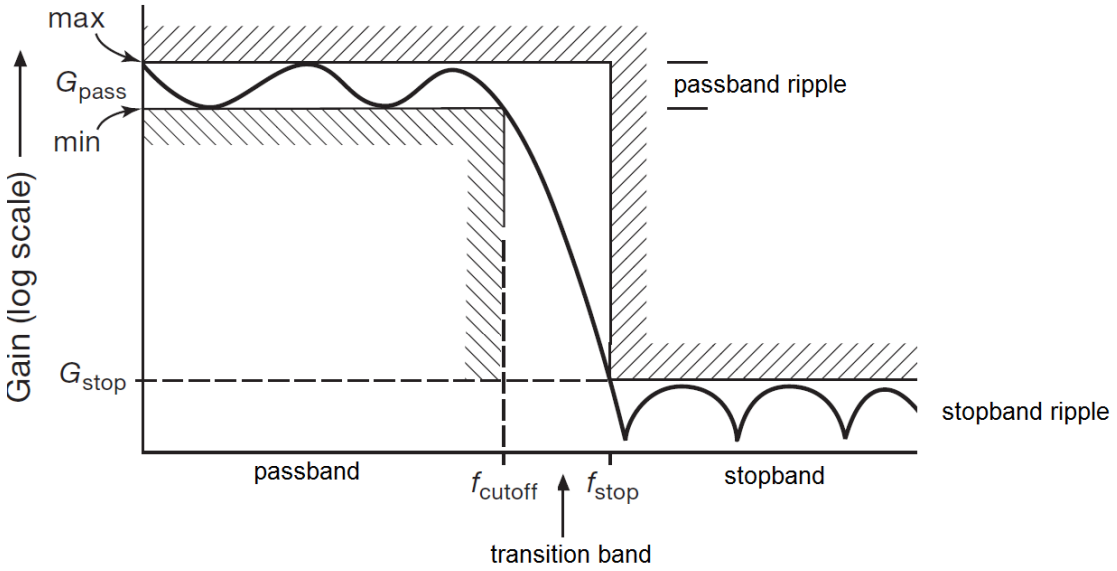

Figure 2.24: filter model

There are filter designs that can optimize each of these characteristics, like the Butterworth filter (maximally flat passband), Chebyshev filter (steepest transition from passband to stopband) and Bessel filter (maximally flat time delay), we chose Chebyshev filter.

The amplitude of Chebyshev low pass filter is given by equation 2.12 [14].

$$\frac{V_{out}}{V_{in}} = \frac{1}{[1+\varepsilon^2 {C_n}^2 (f/f_c)]^{1/2}} \tag{2.12}$$

Where C_n is the Chebyshev polynomial of n order, f_c is the cutoff frequency and ε is a constant called the ripple factor.

The reason of choosing this type of filter is to maintain a sharper transition, with a pass band ripple of $0.1dB$ (which is acceptable for our application) and cutoff frequency of $10.5MHz$, we kept a $0.5MHz$ ($10.5Mhz - 10Mhz$) as a safe range to avoid the effects of the uncertainty of the filter components .

Reducing the second harmonic (located at 30 MHz) by $50dB$, is enough for most of professional uses of the GPSDO.

And that gives :

- Pass-band ripple : $R_p = 0.1dB$
- Stop-band frequency: $\Omega_s = 3$ normalized to $10MHz$

- Pass-band frequency: $\Omega_p = 1.05$ normalized to$10MHz$
- Stop-band Attenuation: $A = 50dB$ or $A = 3.16.10^{-3}$
- Output impedance $R = 50\Omega$

Now, the next step is to determine the suitable order for this filter by Equation 2.13 .

$$N \geqslant \frac{\cosh^{-1}\sqrt{(A^2-1)/\varepsilon}}{\cosh^{-1}(\Omega_s/\Omega_p)} \tag{2.13}$$

Where N is the filter order , and $\varepsilon = \sqrt{10^{R_p/10}-1}$.
Which gives a result between 4 and 5 , so we select $N = 5$ as a filter order[14].

5 order Chebyshev low pass filter can be made by two different configuration, which are :

- In series branch (2 capacitors and 3 inductors).
- Shunt branch (3 capacitors and 2 inductors).

And we used the second one as figure 2.25 shows.

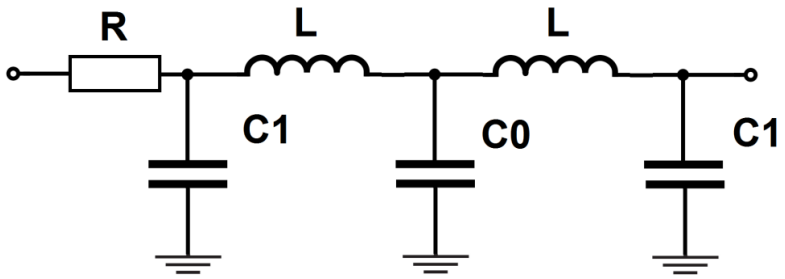

Figure 2.25: Filter schematic

To determine the values of that filter, we use a table of filter element values for Chebyshev filter of $0.1dB$ ripple and $N = 5$, which consists of :

$g_0 = g_4 = 1.1468$, $g_1 = g_3 = 1.3712$, $g_2 = 1.9750$ and $g_5 = 1$

This values are normalized to $f_c = 10.5MHz$ and $R = 50\Omega$ by scaling the pervious values to the actual ones, it gives the results shown in 2.14 , 2.15 , 2.16 [14].

$$C_1 = \frac{g_0}{R \times 2\pi f_c} \approx 347.65pF \tag{2.14}$$

$$C_0 = \frac{g_2}{R \times 2\pi f_c} \approx 598.72pF \tag{2.15}$$

$$L = \frac{R \times 2g_2}{\pi f_c} \approx 1.039\mu H \tag{2.16}$$

Using the standards values it changes to : $R = 47\Omega$, $C1 = 360pF$, $C0 = 560pF$, $L = 1uH$

2.10 Power supply

This part consists in building the power supply unit for the circuit, so first, we start by gathering information about all of the power requirements of all the components, for the voltage supply :

- All of the integrated circuits (phase detector, frequency divider , Schmitt trigger, the microcontroller used for the display) and the GPS module we need 5 volts dc power supply.
- For the VCO, a DC supply between 11 and $13.5V$ is required (we choose 12V source supply in this case).
- And 20-30V for the oven circuit (so 24V works fine).

So in this case, 3 types of power sources are required, now the next step is to calculate the maximum current, that might be reached for each power source :

- The maximum current supply for the GPS module is 230mA , 50mA for the phase detector, 50mA for the Schmitt trigger, and less than 1mA for the two microcontrollers, by summing all together the required current should be less than 350mA for the 5V source.
- For the VCO oscillator only 40mA is needed for the 12V source.
- The 24V source is only for the oven of the VCO, and the maximum current it reaches in the warm up mode is 500mA, which takes less than 10min when it's powered up, and 100mA , when the desired temperature is reached.

In this case, we used one transformer, which can deliver 9V , 18V and 27V , from 230V of the grid lines in its primary, and a rectifier for each secondary which consist of diode bridge of 4A and a capacitor in parallel , followed by 3 different regulators 5v (LM7805) , 12v (LM7812), and 24V(LM7824) which can support up to 1A and 36v as an input voltage, to calculate the capacitors, we use the rule of $Q = 1000\mu F/A$, which means for 1A power source you need $1000\mu F$ capacitor as a filter, or for a better precision, we use formula 2.17 [11].

$$C = \frac{I \times t}{U} \tag{2.17}$$

Where :

- C is the capacitance to be calculated.
- I is the maximum output current.
- t is the period of the peaks equal to $1/(50Hz \times 2) = 10ms$.
- U is the ripple level, it can be calculated by subtracting the regulator voltage input from the rectifier voltage output.

2.10.1 5V source

The output of the transformer $9Vrms$, which means the output of the rectifier peak to peak is $9\sqrt{2} - 0.7 \times 2 \approx 11.3V$, the subtracted 0.7v is the voltage drop of each diode.

And the capacitance is calculated 2.18 .

$$C = \frac{(10ms \times 350mA)}{(11.3V - 7V)} \approx 808.7\mu F \tag{2.18}$$

In this case we used $2.2mF$ capacitance which can support $25V$ for a better filtering

2.10.2 12v source

The same process is applied and it gives2.19

$$C = \frac{(10ms \times 40mA)}{(18\sqrt{2}V - 0.7V \times 2V - 14V)} \approx 40\mu F \tag{2.19}$$

we used $470\mu F$, $35V$ capacitor in this case .

2.10.3 24v source

$$C = \frac{(10ms \times 500mA)}{(27\sqrt{2}V - 0.7V \times 2V - 26V)} \approx 470\mu F \tag{2.20}$$

This power source does not affect the system, because it is only used for the oven, hence it does not need to be very stable, so using $470\mu F/50V$ capacitor is sufficient. And finally, each output of the regulators is attached to a capacitor in parallel to reduce the noise. All of the power circuit is summarized in the Figure 2.26.

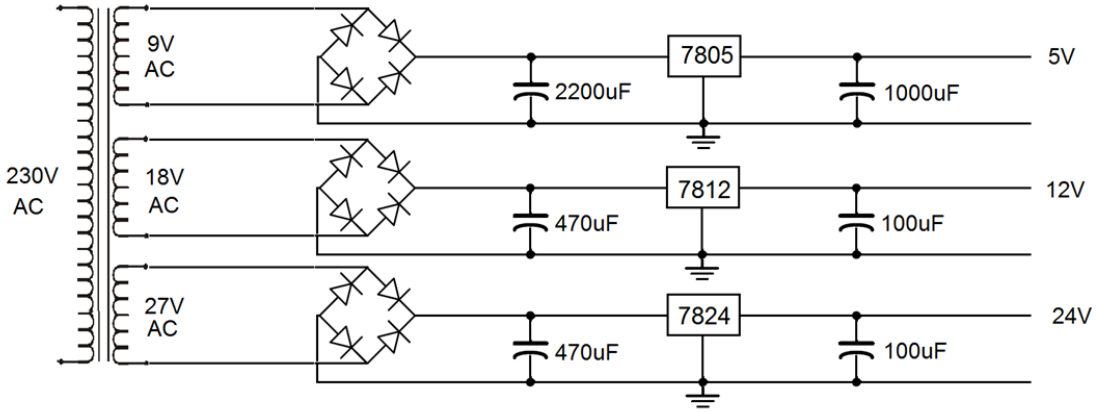

Figure 2.26: fpower supply schematic

After assembling this circuit, now we should see if there are any heat problems of the regulators according to their power dissipation, so first we calculate the maximum temperature the regulators can reach in the previous circuit, and then compare it to the maximum temperature they can resist to decide if placing the heat sinks is required.

According to the data-sheet, the LM78xx series has a thermal resistance junction-ambient of $\theta_{(j-a)} = 19°C/W$ for the TO-220 package, which we are using, and the maximum operating temperature is $T_{max} = 125°C$, if we assume that the external temperature is $T_a = 40°C$ in worst cases, for each regulator, we apply the formula 2.21 , which consists in their temperature without heat sinks in the operation mode.

$$T = V \times I_{max} \times \theta_{(j-a)} + T_a \tag{2.21}$$

With V is the voltage drop at the regulator level, which is the difference voltage between its input and output. I_{max} is the maximum current that can flow through the regulator, $V \times I_{max}$ is their power dissipation, which is transformed to heat.

Now we have:

- For LM7805: $T = (11.3-5) \times 0.35 \times 19 + 40 \approx 82°C$ .In this case the regulator can not reach its maximum temperature, but adding a heat sink is better to reduce it, and avoid its effect on other components.
- For LM7812: $T = (24.8-12) \times 0.04 \times 19 + 40 \approx 50°C$ .On this one the temperature shouldn't be a problem.
- For LM7824: $T = (37-24) \times 0.4 \times 19 + 40 \approx 137°C$ .As we can see it can reach the maximum temperature, which requires a heat sink.

And finally, we add a led indicator for each power source, to indicate the existence of the power.

2.11 Conclusion

The diagram we choose for our project was adapted according to the specifications of our main devices (GPS receiver + VCO), and this diagram can be adjusted in several other ways.

The parts of the GPSDO are quite simple to realize, we studied their design during this chapter, and we will simulate their behavior in the next chapter.

Some of the details of the PLL were neglected such as ; the time it takes for the PLL to stabilize, these details were neglected because of their irrelevancy in this project.

A good knowledge of the GPS behavior can push the performances of our device further away .

Chapter 3

Simulation and Implementation

3.1 Introduction

In this chapter, we will begin our implementation; first we simulate the circuit as it was mentioned in the second chapter.

The parameters of the GPSDO will be simulated one at the time, using different softwares (easyDEA, MATLAB simulink, proteus, ltspice).

At the end, we will give the complete schematic, first in the EasyDEA (online software), then, we will present the real circuit.

3.2 Simulation

3.2.1 Schmitt trigger

We simulated the circuit (Figure 2.14)on software EASYDEA, and it gives the result in Figure 3.1.

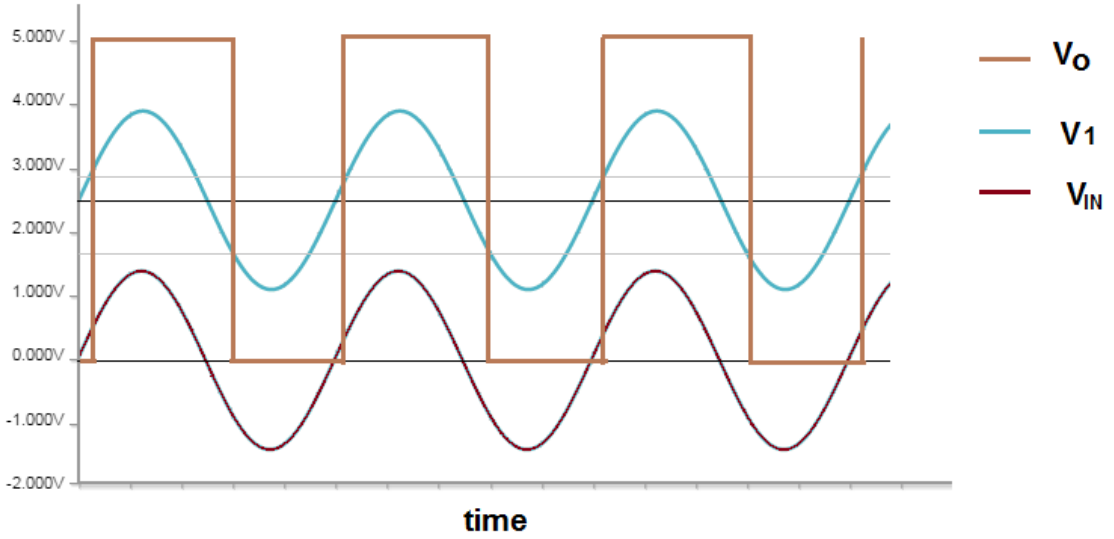

Figure 3.1: The plots of the schmitt trigger circuit from EASYDEA

The plot (Figure 3.1) gives three waveforms (V_{IN} of the signal coming out of the VCO , V_1 the signal shifted, V_0 the square wave signal coming out of the schmitt trigger).

The most important feature of this circuit is the offset it feeds to the Schmitt trigger, a problem with the offset may cause an unbalanced duty cycle, that will introduce an additional phase noise.

Remarks

For more accurate result, we did an experimental test by injecting a sin wave to an implemented circuit in a bread board, and it gives a square wave signal with a 50.1% of duty cycle.

3.2.2 The frequency divider

As we mentioned it in the last chapter, we used pragrammed chip instead of a frequency divider, and in order to simulate its behavior we used Proteus software:

We assembled the circuit in Proteus as it is shown in(Figure 3.2).

After starting the simulation, we captured the resulting waveforms on the frequency-meter , we add, for clearer view, a zoom on the signal waveform in (Figure 3.2)

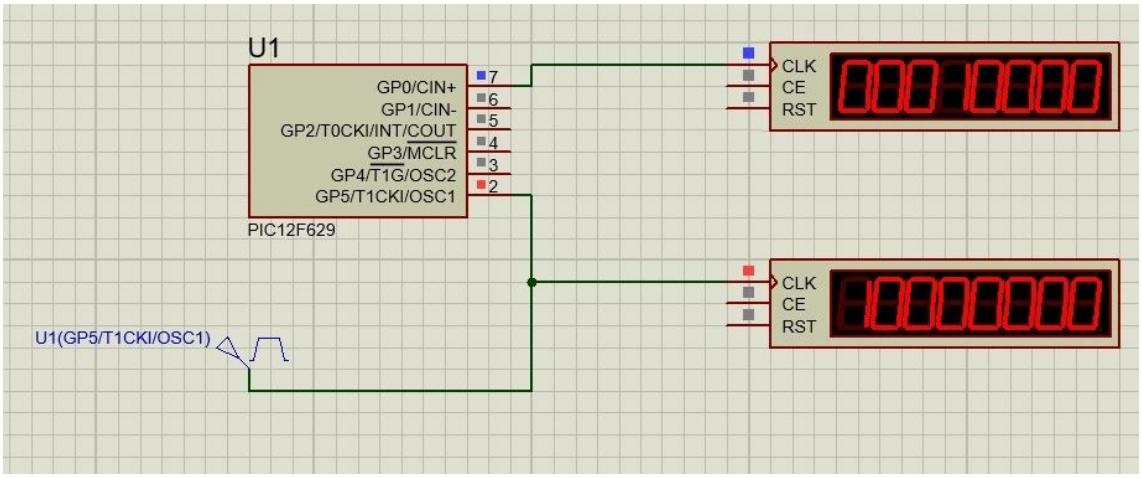

Figure 3.2: Simulation of the divider circuit.

Remarks

- We notice the huge difference in frequency which indicates that frequency has been divided by a 1000 factor.
- The measure must be in real time.

3.2.3 Loop filter

To simulate that filter we used LTspice simulator , after drawing the next schematic (figure 3.3), we applied a square wave signal, whose frequency is $20KHz$ and amplitude 5 volt to visualize the output .

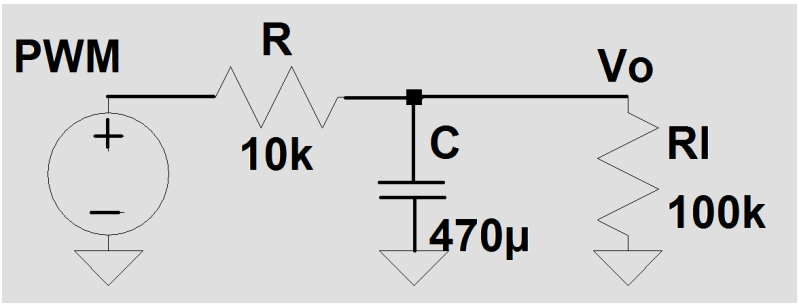

Figure 3.3: loop filter schematic with LTspice

And the V_o output is shown in the Figure 3.4.

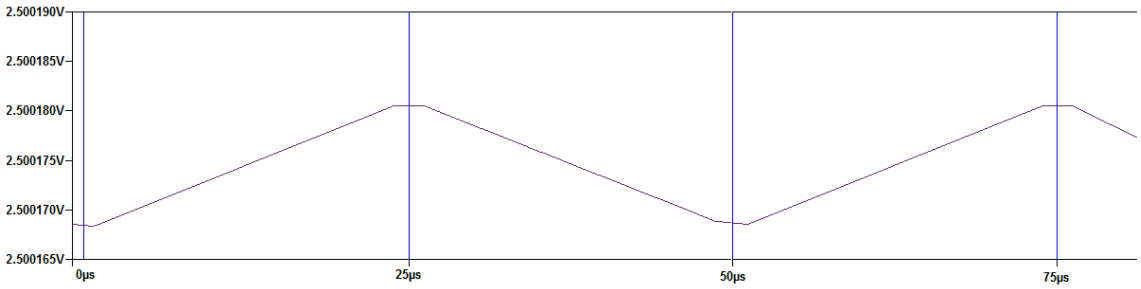

Figure 3.4: The result after simulating the loop filter

As we can see, the residual ripple has been removed in this case.

3.2.4 PLL circuit

The Figure 3.5 shows the diagram of the system simulation on Matlab Simulink.

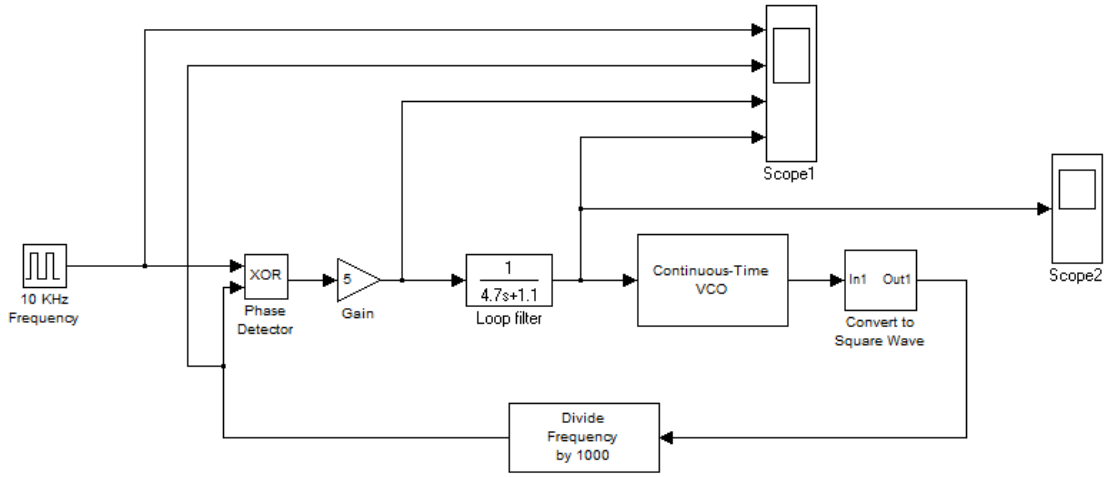

Figure 3.5: Simulation diagram of the PLL entirely

We use the Gain block to amplify the output signal of the phase detector by factor of 5, before injecting it to the loop filter ,because this signal has a 1V amplitude .

The transfer function of the loop filter is indicated by $F(s)$, to calculate its parameters we used the specified components form Figure 2.21 of the loop filter(equation 3.1).

$$F(s) = \frac{1}{1 + \frac{R}{R_L} + RCs} = \frac{1}{1.1 + 4.7s} \tag{3.1}$$

The VCO specifications are inherited from the one we chose, it consist in :

- Quiescent frequency of $10.0000005Mhz$, which is the frequency of the VCO output for 0V at its input
- Input sensitivity is $-0.2HZ/V$, and that supposed to give a $10MHZ$ at the VCO output for $2.5V$ applied to its input .
- The initial phase is specified as a random phase.

The simulation consist of two region: transition region, and stability region .

Scop2 (Figure 3.6) shows the output of the loop filter in first region, which started from the first second.

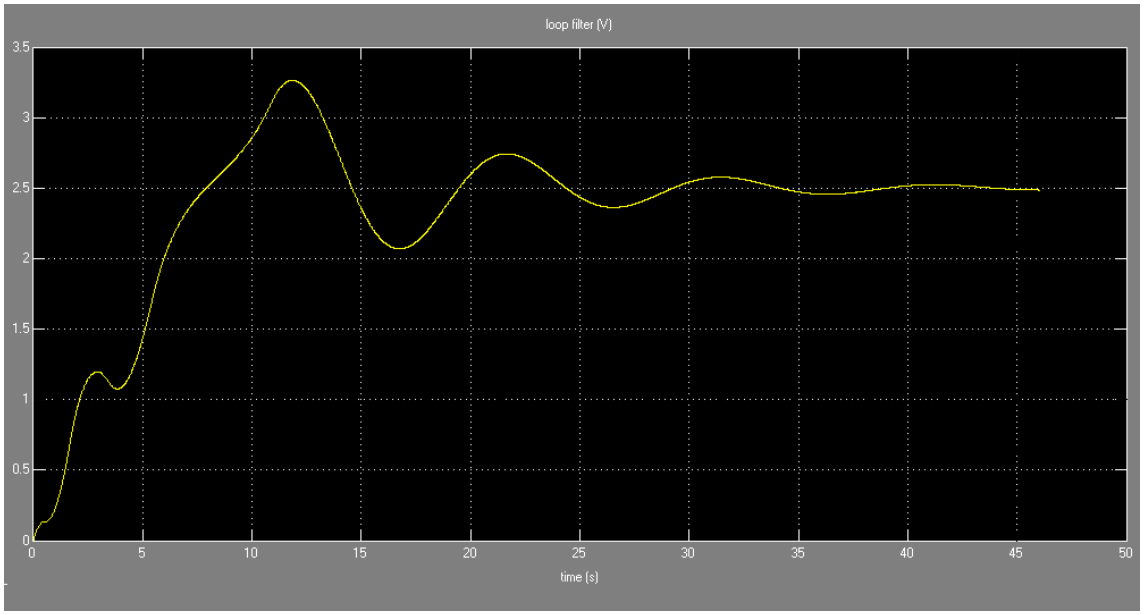

Figure 3.6: Loop filter time domain respond in volts

We can see clearly in the figure 3.6 , that the circuit takes some time to become stable and the filter maintains the $2.5V$ which present the exact $10MHZ$.

The result of scope 1 are in (figure 3.7), this charts show the phase difference between the frequency reference of the GPS module and the divided frequency of the VCO output, and they also show the outputs of phase detector the loop filter.

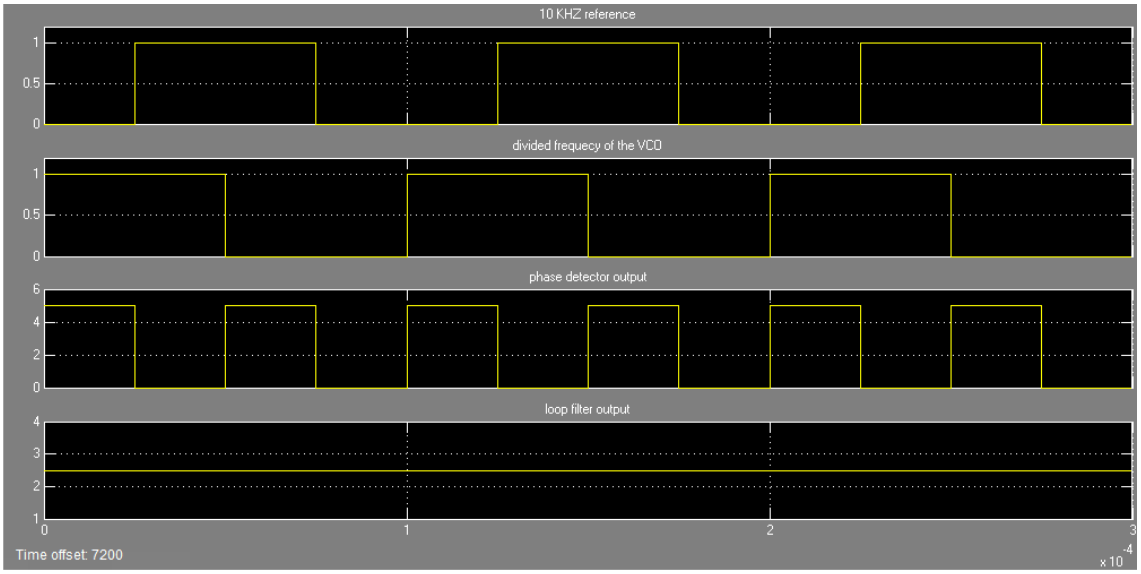

Figure 3.7: Simulation results after 2 hours

This result is only to show this signals in the region of stability, which is approximately 2 hours of running.

This result is exactly as expected, we managed to make $2.5V$ of the input voltage reference as the exact value, to make the VCO produce an exact $10MHZ$ in the stability region. The phase between the 2 inputs of the phase detector is maintained to 45° to produce PWM signal of 50% duty cycle which gives $2.5V$ on the average.

3.2.5 The analog filter

In order to simulate our analog filter, we assembled our circuit on the LTSPICE software as it shown in Figure 3.8.

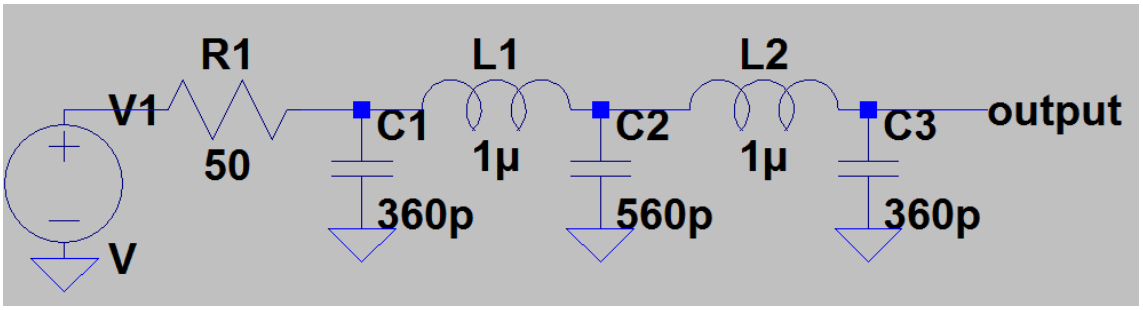

Figure 3.8: Analog filter circuit on LTspice

Then we started the simulation for two possible output charges :

- 50 ohm charge (Figure 3.9).
- open circuit(Figure 3.10).

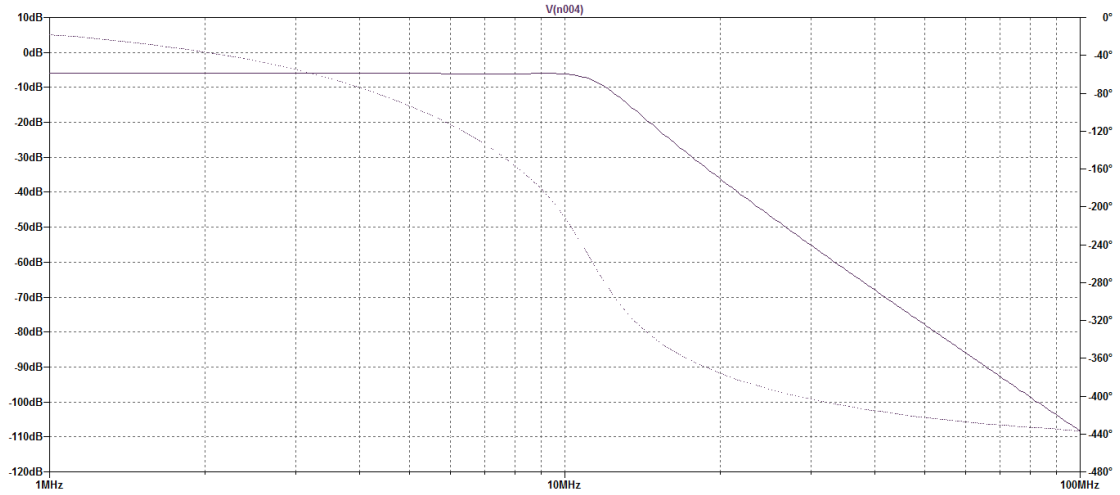

Figure 3.9: Filter response for 50 ohm load in the output

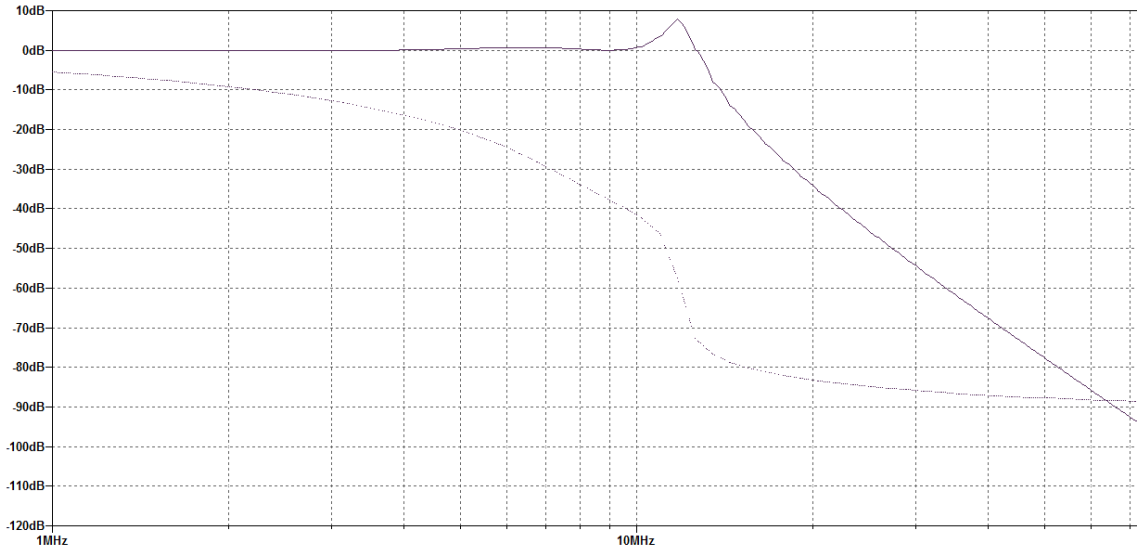

Figure 3.10: Filter response for open circuit

In both cases, the filter attenuates the 30Mhz harmonic by more than 50dB, and that is the desired results from the design process of the filter in chapter 2.

3.3 The final schematic

The figure 3.11 shows the final schematic for the implementation.

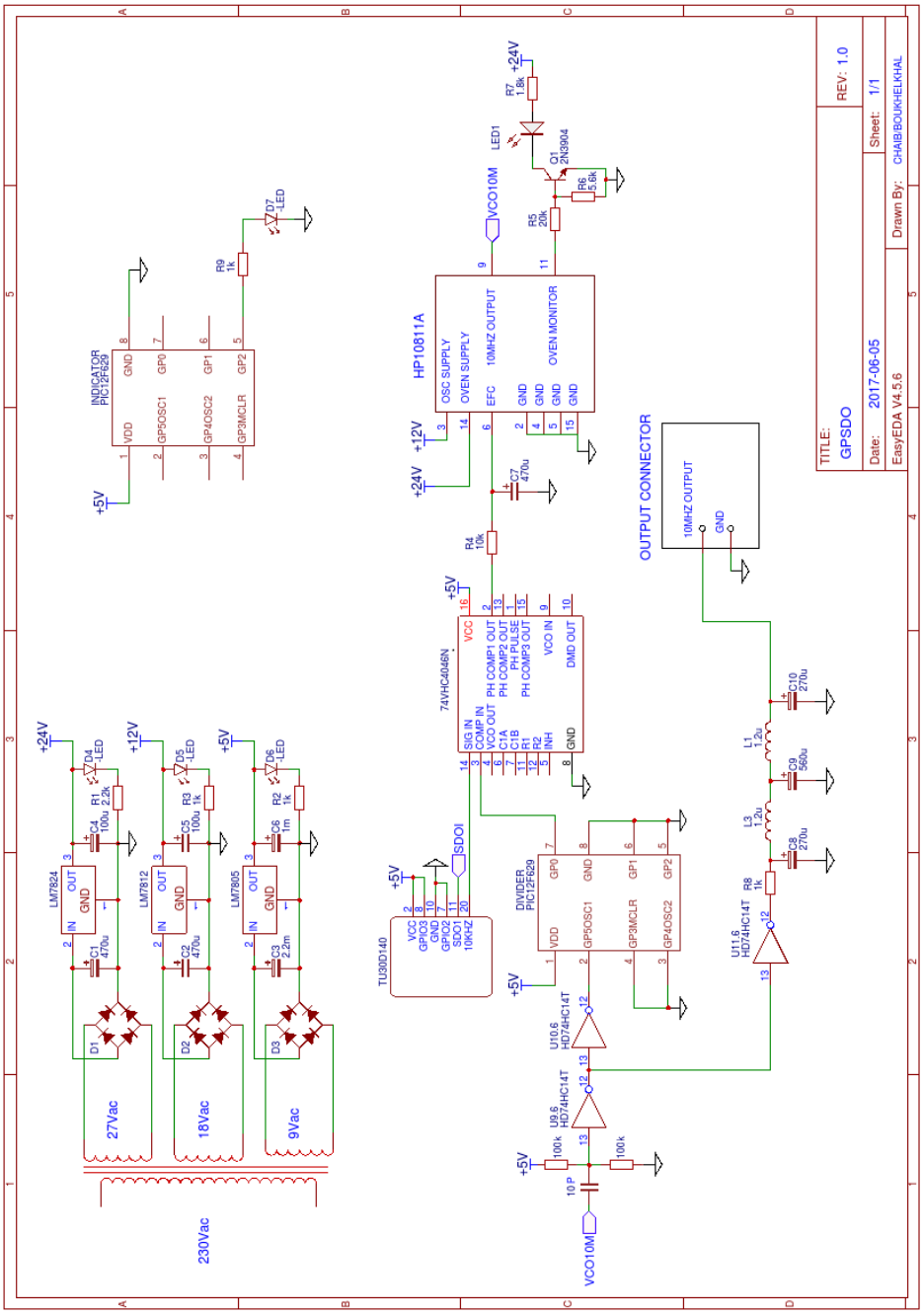

Figure 3.11: Circuit schematic

After trying the circuit on bread board, connecting it to the necessary power supplies, and taking some measurements, it worked as expected.

Now, the next step is to implement the circuit ,first, we started by mounting all the integrated circuits(12F629, 4046, HD74HC14), the two filters on the strip board in a suitable way ,and soldering all of the components as Figure 3.12 shows, then we solder the 3 power supplies on 3 different pieces of strip board.

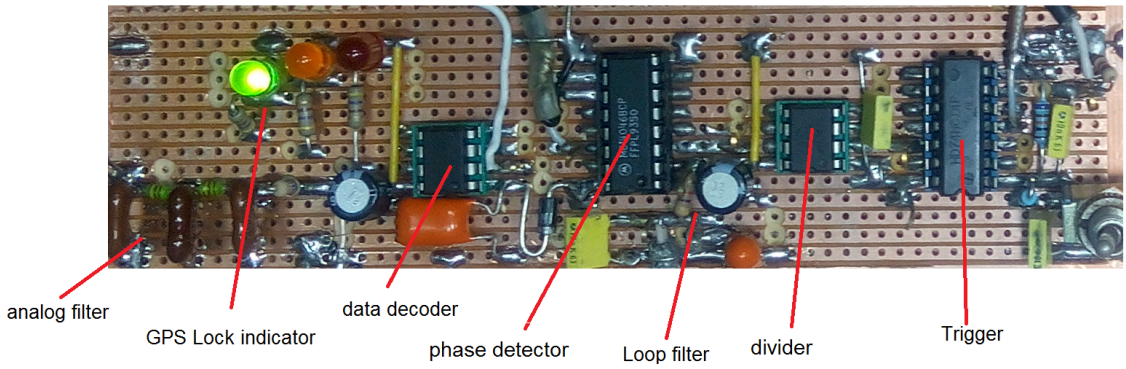

Figure 3.12: Implemented strip board circuit

To minimize the noise, we placed all of the elements (strip board, OCXO, GPS module and the transformer) over plane of copper, and used it as a ground plane,we managed to place the components very close to each other to avoid the long connections, except for the transformer to avoid its magnetic interference with the rest of the circuit.
Figure 3.13 shows the final circuit.

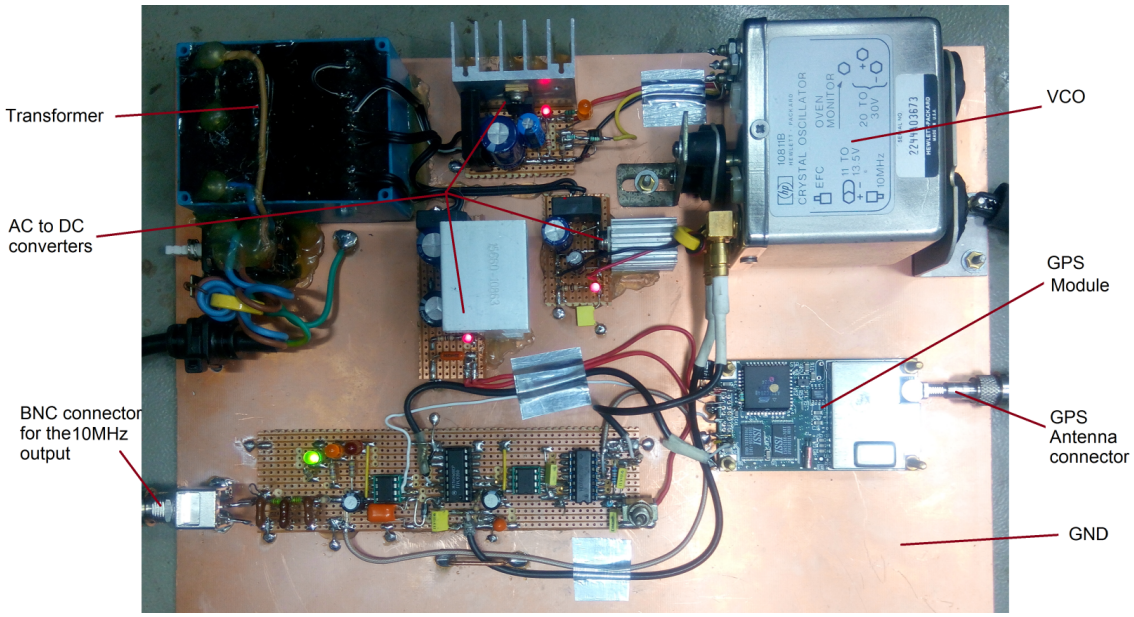

Figure 3.13: final circuit

3.4 Conclusion

This chapter treats the process of simulating and implementing the circuit of GPSDO, starting by simulating the global circuit, and each element if possible, and finally the implementation of the whole circuit, tests and results will be in next chapter.

Chapter 4

Tests and Results

4.1 Introduction

Once the implementation is finished, we verify each connection and fix the bad ones , then we connect the GPS antenna and power up the circuit, the final step is to do the experimental tests :

- Check if all of the elements are working properly.
- Verify the frequency of the output signal.
- Check the noise at the output.
- Finally, determine the power consumption of the whole device.

4.2 Functionality check

In the first second of powering the circuit, the measured frequency was unstable for about 40 min, then the pll locked and the frequency stabilized, the reasons of the 40 min delay time are :

- The GPS module takes some time to lock to the GPS signals and calibrate its own clock, this time depends on the power of the captured signals from the satellites, and that is why using a good antenna is preferable.
- The VCO takes around 10 min to warm up to a certain range of an internal temperature .
- And finally the time the PLL needs to lock .

To check if the system is working as the simulation, we measure the signals of the inputs of the phase detector, its output and the VCO input using an oscilloscope ,Figure 4.1, first one represents the signal that comes from the GPS module , second one from the divider ,third one the phase detector and the last one is the control voltage of the VCO (loop filter output), respectively from top to bottom of Figure 4.1 .

Figure 4.1: Visualizing the signals on the oscilloscope

This results is similar to the simulation, the phase between the 2 inputs of the phase detector is 90°as expected which confirms the functionality of this device .

To measure the frequency output we used a frequency counter calibrated by a professional GPSDO that has an uncertainty of $1mHz$, which gives the measurement $10MHz \pm 1mHz$(or $10MHz \pm 10^{-10}\%$), that is very accurate for numerous applications in telecommunication; that needs a frequency standards, and for calibration purposes.

4.3 Signal properties

This section consist in checking the noise on the output signal , this information is very necessary for some applications, for example, some devices have a noise limitation for the external frequency base, to prevent any noise problem on the system .

Figure 4.2 is the 10MHz signal on time domain, which is a sine wave with some noise, this noise can be explored in the spectrum of the signal.

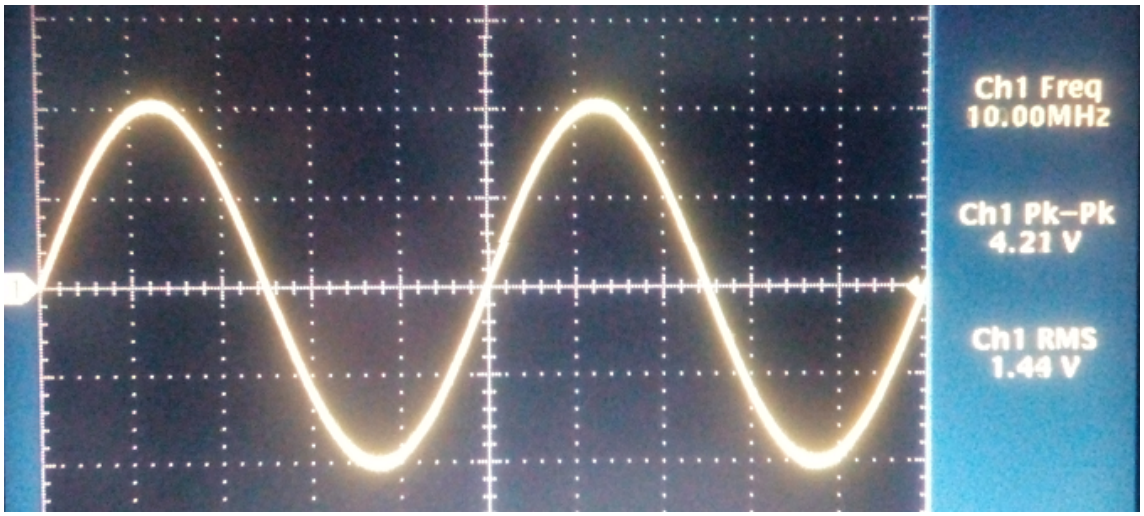

Figure 4.2: GPSDO output signal

Figure 4.3 shows the spectrum of that signal,it is measured by spectrum analyzer from the main frequency ($10MHz$) to $10.1MHz$, the maximum noise is reduced about $58dB$ compared to the main frequency for $10Hz$ bandwidth, to measure the phase noise we need a phase noise analyzer or spectrum analyzer, that can operate with $1Hz$ bandwidth.

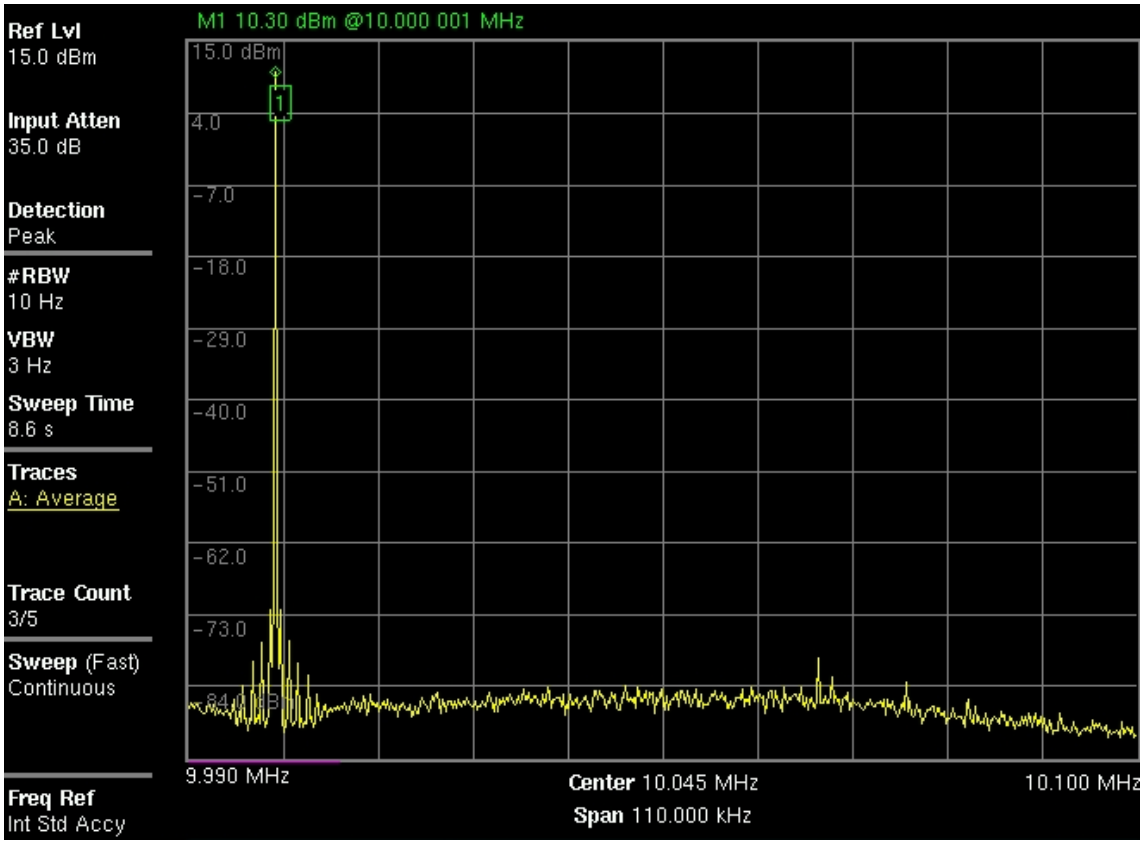

Figure 4.3: Spectrum of the output signal

4.4 Frequency accuracy measure

Using a frequency meter connected to an external frequency reference, we were able to measure the degree of precision that our time frequency presents.

The frequency meter in this measure takes samples during 30 seconds, and it can reach a precision of 10^{-10} if it is connected to an external time reference source. You can see the measurement below in figure 4.4.

Figure 4.4: Frequency measurement

We can see from the figure that the frequencies are perfectly matched, and the precision reaches 10^{-10} order, the results are quite satisfying and are not very far from the expected ones.

4.5 Power dissipation

Measurement about power dissipation:

- The 5 volt source delivers about 166 mW.
- 12 V source delivers 540 mW for the VCO .
- 24 V source delivers 13.2W when the oven is on, and that happens only in the few first minutes at the beginning, and 2.28W when it is off.

This gives about 14W as maximum, without the losses of the transformer and the AC to DC converters, and 3W in most of the time.

The total power needed of the whole device is 22W in the first few minutes, and 10W when the VCO reach the desired temperature.

4.6 Conclusion

In this chapter, we saw only some basic experimental tests on this device, which gives a comfortable results, and verifies the good functioning of this GPSDO .

For better measurement, we need other professional measure instrument like phase noise analyzer, to measure the phase noise , this information is necessary in some application, because it defines the frequency accuracy and stability in short term.

For long time stability, we need to calibrate this device by taking it to a calibration laboratory, and verifying the accuracy and stability of the frequency for one day.

And finally, for the results of our measurement, we can say that the frequency standard can be used as :

- A standard reference for the laboratory, to use it as a precise time base for data acquisition.
- External oscillator for the devices that needs a very accurate 10MHz external frequency reference ,as most of the professional telecommunication instrument like transceivers and modems, and measurement instruments; like frequency counters, function generators, network analyzers ...etc ,
- A reference to calibrate the local oscillators of the instruments, in theory, this device is traceable to UTC time and has the same accuracy, so every instrument has an oscillator that can be calibrated with this device, but in this case, it should be calibrated and documented by a calibration laboratory.

General Conclusion

The precision in electronics is a serious matter, the development of different technologies is primary due to the degree of precision we can attain.

One of the most encountered features in most of the devices is the frequency, and during many years, the challenge was to find a time reference, that would be of high precision on the one hand, and high fidelity on the other. The only oscillators that have these characteristics are the atomic clocks, the problem as we mentioned earlier in chapter 1 is that they are very expensive.

The engineers turned away from these expensive oscillators, and they invested in designing complex circuit which they will call later as OCXO and TCXO, although they yield very precise frequencies, they were not as good as the atomic clocks.

The GPSDO was a simple innovative idea that revolutionized this field; this idea is a very insightful one since it makes you conscious of the possibilities that exist in electronics.

We began our work by looking at similar projects, and trying to understand how and why they used their components a certain way, then, we started our design roughly by taking a diagram to work on, after that we worked on improving every stage apart from one another, the project then worked after some efforts.

Then, we made the necessary computation to see ideally how the GPSDO behaves, and to confirm the computation, we made the available measurement, and as a final step, we searched for the different problems that could prevent a good functioning of the GPSDO, we ended up having the two side of the coin, we collected these pros and cons:

Pros:

- The GPSDO delivers a very precise and stable frequency for a decent price.
- It is easy to implement, and require very few components.
- It has no drift, since it is continuously traceable.

Cons:

- The precision of the GPSDO is directly linked to the GPS signal, therefore any interference between the GPS receiver and GPS satellite gives us false data.

- This device requires an antenna, besides, it should be connected to more than three satellites, so there should be a clear view between GPS antenna and the sky.

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Appendix A : Frequency divider code

```
_interrupt: MOVWF R15+0 ;1cycle + 3 cycles of interrupt delay
SWAPF STATUS+0, 0 ;1cycle
CLRF STATUS+0 ;1cycle
MOVWF ___saveSTATUS+0 ;1cycle MOVF PCLATH+0, 0 ;1cycle
MOVWF ___savePCLATH+0 ;1cycle
CLRF PCLATH+0 ;1cycle
MOVF _l+0, 0 ;1cycle
MOVWF GPIO+0
MOVLW 201 ;1 cycle
MOVWF TMR0+0 ;1 cycle+ 2 cycles (sync)
+(256-201)*2(prescaler) MOVLW 160 ;beginning of the counter
MOVWF INTCON+0
MOVF _l+0, 0
IORWF _l+1, 0
MOVLW 1
BTFSS STATUS+0, 2
MOVLW 0
MOVWF _l+0
MOVWF _l+1
MOVLW 0
MOVWF _l+1
L_end_interrupt:
L__interrupt3:
MOVF ___savePCLATH+0, 0
MOVWF PCLATH+0
SWAPF ___saveSTATUS+0, 0
MOVWF STATUS+0
SWAPF R15+0, 1
SWAPF R15+0, 0
RETFIE
_main:
MOVLW 160
MOVWF INTCON+0
MOVLW 128
MOVWF OPTION_REG+0
MOVLW 7
MOVWF CMCON+0
MOVLW 255
MOVWF OSCCAL+0
MOVLW 62
MOVWF TRISIO+0
MOVLW 201
MOVWF TMR0+0
BCF GPIO+0, 0
```

```
L_main0:
L_end_main:
GOTO $+0
```

Appendix B : TU30 GPS receiver pins

Pin #	Name	Description	Pin #	Name	Description
1	PREAMP	Preamp power input	11	SDO1	Serial data output port #1
2	PWRIN_5	Primary +5 VDC power input	12	SDI1	Serial data input port #1
3	VBATT	Battery backup voltage input	13	GND	Ground
4	N/C	Reserved (no connect)	14	N/C	Reserved (no connect)
5	M_RST	Master reset input (active low)	15	SDI2	Serial data input port #2
6	N/C	Reserved (no connect)	16	GND	Ground
7	GPIO2	NMEA protocol select	17	GND	Ground
8	GPIO3	ROM default select	18	GND	Ground
9	GPIO4	Reserved (no connect)	19	TMARK	1 PPS time mark output
10	GND	Ground	20	10KHZ	10 kHz clock output

Table 4.1: TU30 GPS receiver pins

Appendix C : Reciever serial port configuration truth table

NMEA Protocol Select (Pin 7)	ROM Default Select (Pin 8)	Result
0	0	NMEA message format; host port communication settings = 4800 bps, no parity, 8 data bits, 1 stop bit. The receiver operates from default initialization values stored in ROM and outputs the default NMEA message set from ROM.
0	1	NMEA message format; host port communication settings = 4800 bps, no parity, 8 data bits, 1 stop bit. The receiver selects the default NMEA output message set and uses initialization values from the data stored in SRAM or EEPROM (Note 1).
1	0	Binary message format; host port communication settings = 9600 bps, no parity, 8 data bits, 1 stop bit. The receiver operates from default initialization values stored in ROM.
1	1	Data stored in SRAM or EEPROM determines message format, host port communication settings, and default message set (Note 1).
Note 1: For further information, refer to the description of the ROM Default Select pin (J1-8) below.		

Table 4.2: Reciever serial port configuration truth table