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Design of an Ultrasonic-based relative position measuring system

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LIST OF ACRONYMS

ADC   Analog to Digital Converter

ARM   Acorn RISC Machine

AVS   Artificial Vision System

CCD   Charged Coupled Device

DGPS   Differential GPS

DSP   Digital Signal Processing

FFSU   Forced Frequency Switch-Up

GPS   Global Positioning System

GPT   General Purpose Timer

JFET   Junction-gate Field Effect Transistor

LDBW   Largest Detection BandWidth

NSS   Noise Suppression System

PPL   Phase-Locked Loop

RF   Radio Frequency

RFID   Radio Frequency IDentification

RX   Receiver Node

RXM   Receiver Module

STUFF   System Technology for UAV Formation Flight

TD   Tone Decoder

TOA   Time Of Arrival

TOF   Time Of Flight

TX   Transmitter Node

TXM   Transmitter Module

UAV   Unmanned Aerial Vehicle

UWB   Ultra Wide Band

VCO   Voltage Controlled Oscillator

ABSTRACT

As part of a new project, named STUFF (System Technology for UAV Formation Flight) promoted by the Department of Aerospace Science and Technology of Politecnico di Milano, the following research, investigates and proposes a design, for a device aimed to measure distances, between two UAVs. With the final purpose of becoming a flight formation instrument, intended for small and light UAVs, ultrasound technology emerged, among others, to be a valuable solution. The system consists in a transmitter and a receiver module to be mounted on the leader and wingman aircraft. In order to retrieve a measure, the Time Of Flight (TOF) is computed comparing the signal with a synchronous GPS message event. A 40 kHz square wave, digitally generated, gets amplified by two 555 timers in push-pull configuration and radiated through a 16 mm ultrasonic transducer. The technique used to detect the signal on the receiver module, is based on an analog Tone Decoder which analyzes a normalized input and enables its output when frequency and amplitude fall in a preset range. The execution of numerous tests has been necessary not only to tune and calibrate the system, but also to provide data for the formulation of a model for TOF estimation, that ended up to be a comparison between the reference time and the end of the transmitted 40 kHz pulse sequence. A Noise Suppression System (NSS), a Forced Frequency Switch-Up (FFSU) and other strategies have been implemented in order to increase accuracy and availability. The experimental system, at the end of this stage of development, confers good accuracy and ranging, still abiding to the requirements for compact size, light weight and low power equipment. However, future developments are still needed to increase coverage as well as to provide 3D positioning and attitude determination. Moreover, thoughts should be made regarding a conversion to a Digital Signal Processing (DSP) system for a possible boost in acquisition performance.

SOMMARIO

Il seguente documento, si occupa di illustrare la progettazione e la sperimentazione di un sistema, con lo scopo di misurare la distanza tra due Unmanned Aerial Vehicle (UAV), per mezzo di tecnologia a ultrasuoni, finalizzato a diventare uno strumento per il volo in formazione. Il sistema consiste in un modulo trasmittente e uno ricevente montati rispettivamente sul velivolo "leader" e "wingman". Per ottenere una misura, il tempo di volo (time of flight TOF) viene calcolato confrontando il tempo di invio e ricezione del segnale con quello di un messaggio GPS sincronizzato. Si è scelto di affidare il lavoro di acquisizione del segnale ai componenti analogici, consentendo in tal modo di equipaggiare i velivoli con microcontrollori leggeri e a basso consumo. Un'onda quadra a 40 kHz, generata digitalmente, viene amplificata da due "555 timer" in modalità "push-pull" e irradiata per mezzo di un piccolo trasduttore a ultrasuoni. La tecnica usata per acquisire il segnale sul modulo ricevente si basa sull'analisi di un segnale, preamplificato e normalizzato, per mezzo di un Tone Decoder (TD) il quale da' un impulso in uscita quando la frequenza e l'ampiezza cadono all'interno di intervalli preimpostati. La strategia sperimentale ha in primo luogo l'obiettivo di impostare e calibrare il dispositivo, per ottenere la migliore combinazione tra prestazioni e rumore. Secondariamente, i dati ottenuti dagli esperimenti vengono utilizzati per formulare un modello per la stima del TOF, che consisterà nel comparare il tempo di riferimento (GPS) con la fine della sequenza a 40 kHz. Un codice per ridurre l'interferenza dovuta al rumore (Noise Suppression System NSS), un sistema per bloccare l'inerzia meccanica del trasduttore (Forced Frequency Switch-Up FSSU) e ulteriori strategie sono state implementate per aumentare la precisione e la disponibilità del sistema. Il progetto sperimentale, all'attuale stato, conferisce buona accuratezza e portata, pur soddisfacendo i requisiti di leggerezza, piccole dimensioni, e basso consumo. Tuttavia, risultano necessari sviluppi futuri per migliorare copertura e ottenere un posizionamento 3D. Inoltre, è raccomandabile entrare nell'ottica di spostarsi su un sistema di acquisizione digitale del segnale, per aumentare ulteriormente le prestazioni.

CHAPTER 1 - INTRODUCTION

1.1 Introduction and motivation

Fixing the position of an object in space, is always been one of the major aspect of navigation. The concern gets more and more significant when the focus shifts on automatic and accurate navigation systems, specifically in aeronautical environment. The research in this field continuously demand for performance improvement and ad-hoc design in order to satisfy the numerous and individual requirements for a growing number of detailed applications (1).

Specifically, the design of the entitled relative positioning system, comes to address the needs for a safe and efficient formation flight by UAV. One of the simplest configurations used, is where an autonomous aircraft maintain formation with a lead aircraft.

1.2 Potential Technologies and Developments

In order to start considering different approaches to accomplish the task, few requirements are needed. These might be particularly strict, due to safety concerns.

As for every positioning system, accuracy is probably the most significant aspect and for this purpose become essential. Availability, reliability and continuity, then, are crucial, since just few seconds without a usable service, can compromise the mission. Nevertheless, coverage, power required, weight and size are to be taken into account, as we are dealing with a small and light aircraft (about 1m wingspan) (view Figure 1-1).

We analyze now, three possible solutions for relative positioning, trying to figure out if they meet the, still vague, requirements above.

Figure 1-1 Target Aircraft for the entitled relative positioning system

1.2.1 GPS

GPS is a satellite-based absolute positioning system, that require no other than an inexpensive receiver in order to work.

Specifications for many standard GPS receivers for civil use, indicate their accuracy will be within about 3 to 15 meters, 95% of the time (2).

The configuration, in order to provide a relative measurement between two moving objects, would consist of two receivers, mounted on both aircraft, and a wireless link, to transmit the information from the leader to the wingman.

That said, the GPS accuracy provided, by itself, is already unacceptable, moreover it should be doubled, since there are two receivers in play and the specifications for the data-link should be taken into account too.

Even considering a DGPS (Differential GPS), although it might be on the edge of the tolerable accuracy, the necessity of a reference ground base makes it unsuitable for our purpose when the area to cover gets too wide or for unequipped locations.

1.2.2 Artificial Vision System (AVS)

Vision based positioning systems use the same basic principles of landmark-based and map-based positioning, but rely on optical sensors rather than ultrasound, dead-reckoning and inertial sensors. The advantage of these type of sensors lies in their ability to directly provide distance information.

Real world applications envisaged in most current research projects however, demand more detailed sensor information to provide better environment-interaction capabilities. Visual sensing can provide the aircraft with an incredible amount of information about its environment. Visual sensors are potentially the most powerful source of information among all the sensors used. Hence, at present, it seems that high resolution optical sensors hold the greatest promises for positioning and navigation.

The most common optical sensors include laser-based range finders and photometric cameras using a Charge Coupled Device (CCD) arrays (3).

However, due to the volume of information they provide, extraction of visual features for positioning is far from straightforward.

The environment is perceived in the form of geometric information such as landmarks, object models and maps in two or three dimensions. Localization then depends on the following two inter-related considerations:

A vision sensor (or multiple vision sensors) should capture image features or regions that match object models.

These object models should provide necessary spatial information that is easy to be sensed.

That said, advances in artificial vision could achieve accuracies of several centimeters at the expense of having to use an expensive infrastructure with a low modularity and high processing demand. (4)

Albeit accuracy would be fine enough, weight, size and computing power required as well as presumable unreliability due to light reflection force us to bail out.

1.2.3 Radio Frequency System

Systems based on Radio Frequency (RF) signals require fewer infrastructures than other technologies, but have less accuracy. This accuracy is of tens of centimeters for Ultra Wide-Band (UWB) systems based on measurements of Time Of Arrival (TOA) (5), of several meters using Wi-Fi (6) and Radio Frequency Identification (RFID) (7) or tens of meters for

mobile networks (8). Such precision is unacceptable for this application with centimeter accuracy requirements.

1.2.4   Ultrasonic System

In order to retrieve the relative position with another object via ultrasonic technology a self-contained and a co-operative solution have been assessed.

The first does not require the target to be equipped, since it is just responsible for reflecting back the signal. This configuration would be appropriate just for the measure of the absolute distance between them, it cannot provide 3D positioning, thus ineligible.

Instructing, instead, the leader to transmit the signal from different sources (e.g. wingtips) would make trilateration possible.

High expected accuracy, light weight, low power, small sizes promote this layout to be the most suitable.

1.3 Ultra Sound technology

In recent years the use of location information and its potentiality in the development of aeronautical applications has led to the design of many positioning systems based on different technologies. What's emerged from our research, analyzing the most appealing technology, with respect to the aim of this project, is gathered in Table 1

	GPS (DGPS)	AVS	RF	US
Accuracy	** (***)	*****	****	*****
Availability	**	**	****	****
Weight	*****	*	****	*****
Power Consumption	*****	**	***	****
Size	*****	*	****	****

*Table 1: Comparison of possible technologies. Rating= * (bad), ***** (good).*

Furthermore, unlike these technologies, the ultrasound signal has several advantages such as slow propagation speed, negligible penetration in walls and low cost of the transducers.
Ultrasounds are sound waves with frequencies higher than the upper audible limit of human hearing. Ultrasonic devices operate with frequencies from 20 kHz up to several gigahertz and are used in many different fields: object detecting, distance measuring, non-destructive testing, medical imaging, etc. The accuracy achieved by ultrasound is typically of a few centimeters. (9)

CHAPTER 2 - DESIGN

The ultrasound relative positioning system is based on Time Of Flight (TOF) of ultrasonic signal to estimate the distance between a receiver node and a transmitter node.

The ultrasonic signal is transmitted using a carrier frequency of 40 kHz and the TOF measurement is estimated comparing both signals with a synchronized reference time. (view *Figure* 2-1: Ideal TOF estimation

)

In literature, there are several examples of strategies to solve the synchronization problem in wireless sensor networks. Some of them use Radio Frequency (RF) signals, given the negligible propagation delay, other use atomic clocks.

Since the target UAVs are already equipped with a GPS receiver the synchronization can be easily achieved comparing the local time with a GPS message event.

The distance is calculated from the TOF taking into account the speed of sound, thus, a temperature sensor is required to compensate the effect on its estimation.
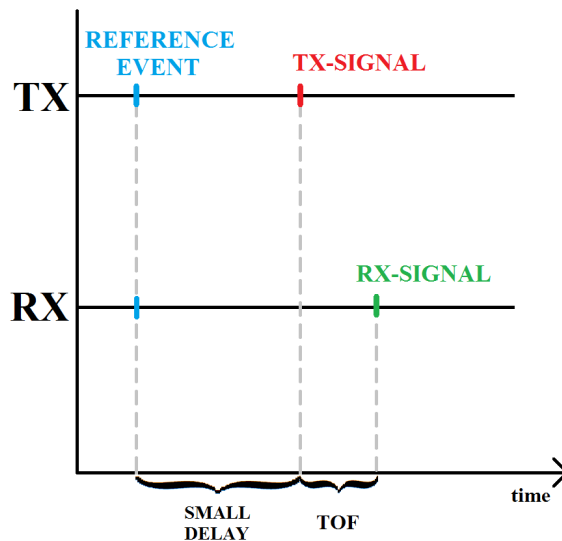
Figure 2-1: Ideal TOF estimation

2.1   Hardware Design

The 1D basic configuration consists in an Ultrasound Transmitter node (TX), an Ultrasound Receiver node (RX), a GPS receiver and a Temperature sensor.

The leader aircraft should be equipped with a Transmitter and a GPS. The transmitter generates a signal and send it synchronously with the GPS clock.

The wingman mounts a Receiver, a GPS a temperature sensor and an air speed data sensor. The Receiver catches the signal, compares the time with the GPS clock, estimates the speed of sound with the information provided by the temperature sensor and corrects for air speed. A schematic overview is represented in Figure 2-2.

Figure 2-2 System Block Diagram

2.2 Components and specifications

Following is provided a brief description of the main components adopted in this project to build the transmitter and the receiver module.

The GPS receiver, the temperature sensor and the air speed data sensor won't be discussed any deeper. From now on it will be assumed that they all provide data ready for use.

2.2.1 OLIMEX STM32-H107 Board

The OLIMEX STM32-H107 is a header board for the STM32F107 CORTEX M3 Microcontroller.
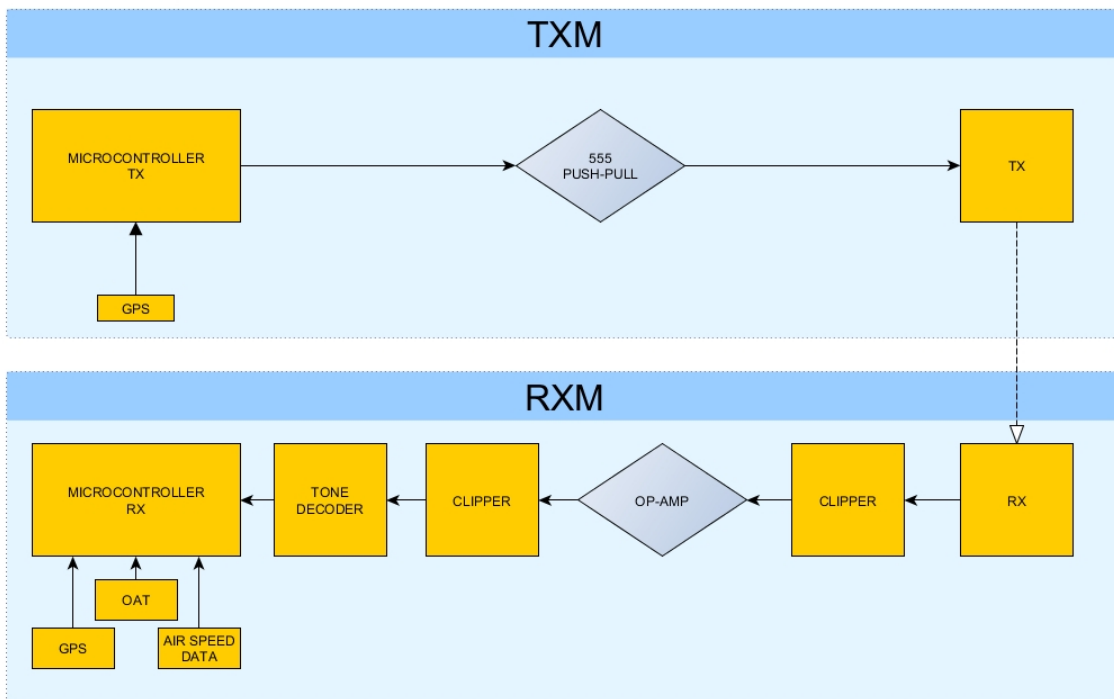
The ARM Cortex-M3 processor is the latest generation of ARM processors for embedded systems. It has been developed to provide a low-cost platform that meets the needs of MCU implementation, with a reduced pin count and low-power consumption, while delivering an outstanding computational performance and an advanced system response to interrupts. (10)

2.2.2 555 Timer as amplifier

The 555 timer is an integrated circuit used in a variety of timer, pulse generation, amplification, and oscillator applications (11).

Configured as amplifier, can source as much as 200mA, but it can increase just positive voltage applied to the trigger, everything below 0V will be clipped out.

2.2.3 Ultrasonic Transducers

Both the receiver and the transmitter (Figure 2-3) share common specifications, more significantly, they have a center frequency of 40 kHz ± 1 kHz, a Bandwidth -6dB of 2 kHz, a Beam Angle -6dB of 55° (view Table 2)

Transducer Specifications	
Center Frequency	40.0 +- 1.0 kHz
Bandwidth (-6dB)	2.0 kHz
Transmitting Sound Pressure Level	120 dB min.
Receiving Sensitivity	-61 dB min.
Capacitance at 1 kHz +-20%	2400 pF
Max. Driving Voltage (cont.)	20 Vrms
Total Beam Angle (-6dB)	55°
Operation Temperature	-30 to 70 °C
Storage Temperature	-40 to 80 °C

Table 2 Ultrasonic Ceramic Transducers 400ST/R160 Specifications (12)

Figure 2-3 Ultrasonic Transducers

2.2.4   LF351 Op-Amp

These low cost JFET input operational amplifiers combine two state–of–the–art analog technologies on a single monolithic integrated circuit. Each internally compensated operational amplifier has well matched high voltage JFET input devices for low input offset voltage. The JFET technology provides wide bandwidths and fast slew rates with low input bias currents, input offset currents, and supply currents. (13). The signal received, depending on source power and distance, might not be strong enough, thus, the necessity for amplification before analysis.

2.2.5   LMC567 Tone Decoder

The LMC567 is a low power general purpose tone decoder. It consists of a twice frequency voltage-controlled oscillator (VCO) and quadrature dividers which establish the reference signals for phase and amplitude detectors. The phase detector and VCO form a phase-locked loop (PLL) which locks to an input signal frequency which is within the control range of the VCO. When the PLL is locked and the input signal amplitude exceeds an internally pre-set threshold, a switch to ground is activated on the output pin. External components set up the oscillator to run at twice the input frequency and determine the phase and amplitude filter time constants (14).

The purpose of the tone decoder in the project is dual: it filters out frequency far from the centered 40 kHz and it marks e clear begin and end of the pulse-sequence received.

2.3 Transmitter Module

The best configuration conceived consists in a OLIMEX STM32-H107 that generates a 40 kHz square wave, amplified by two 555 timers in push-pull mode (view Figure 2-4 and Figure 2-5).
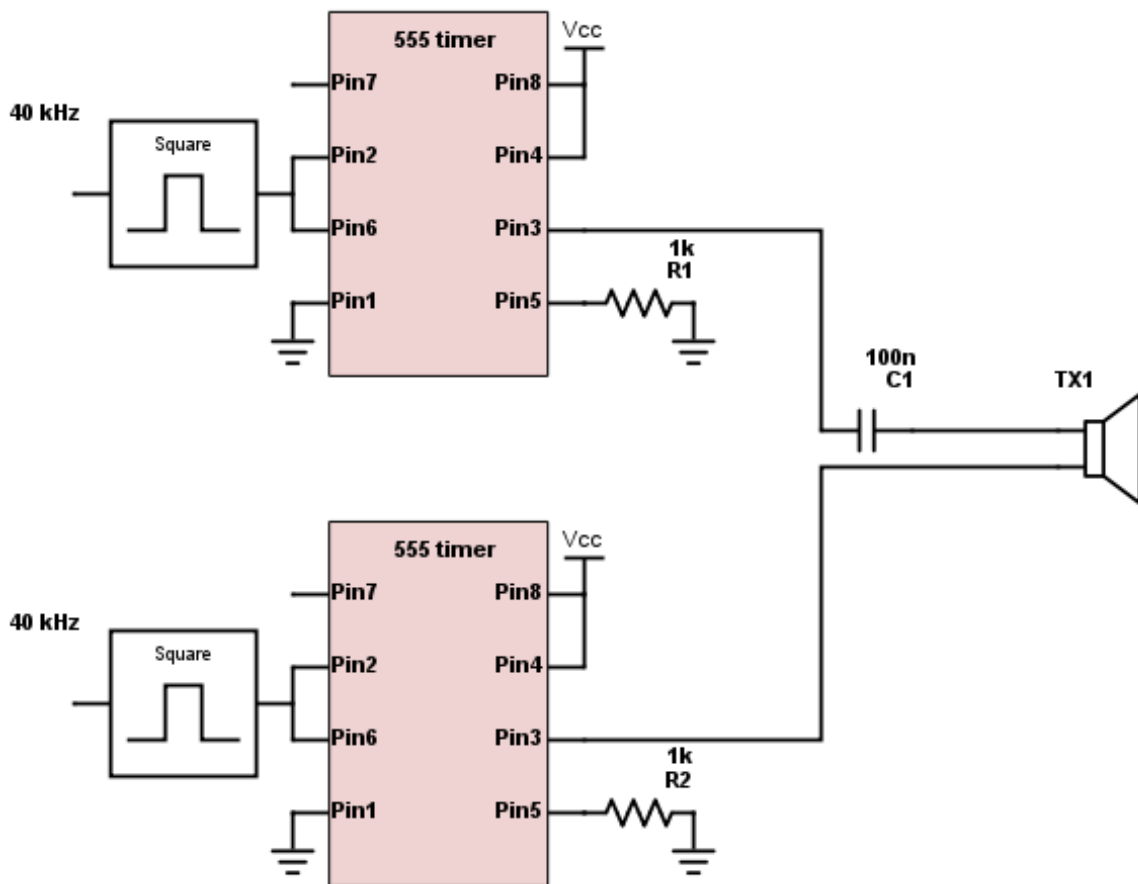
Figure 2-4 Transmitter Diagram
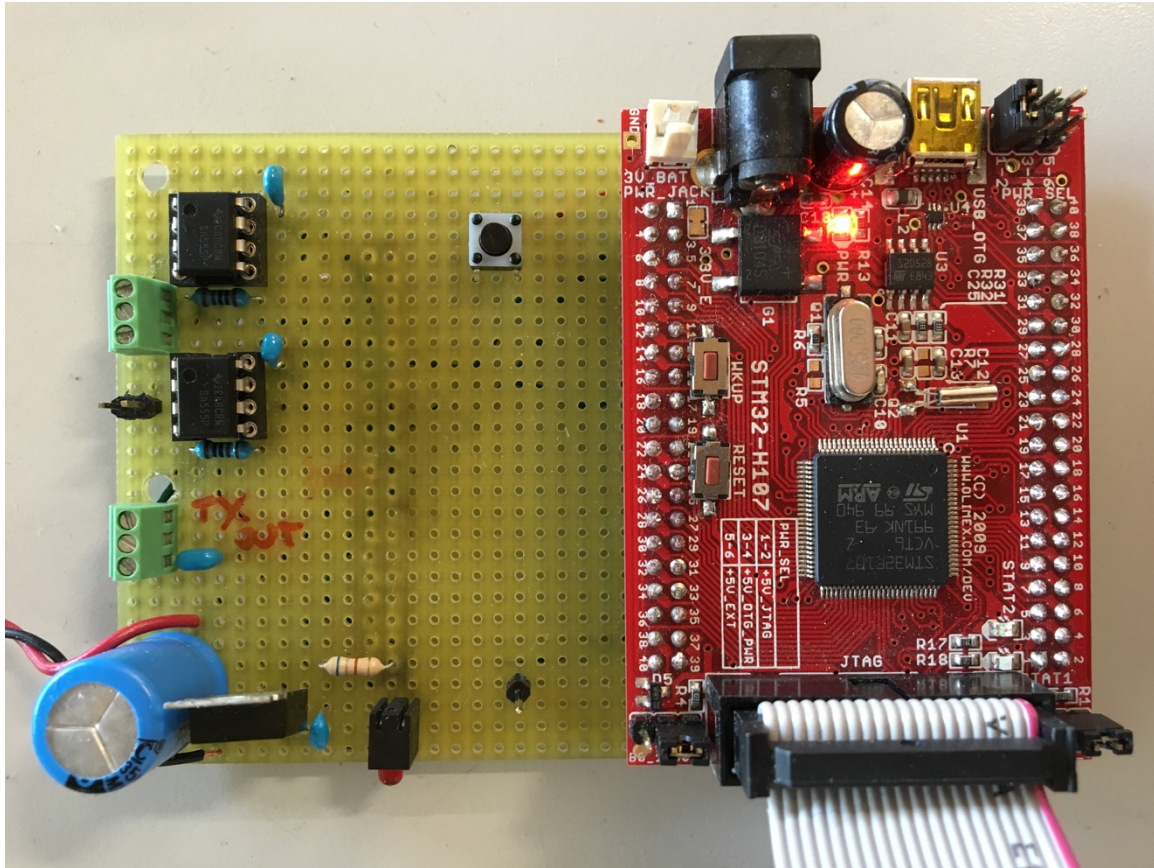
Figure 2-5 Transmitter Module

The generation of the ultrasonic signal is performed using the GPT (General Purpose Timer) module of the microcontroller. Two sequences 180° out-of-phase of alternating 0 and 1 bits are generated at a baud rate equal to twice the resonance frequency of the transducer (80 kbps) with an appropriate duration. The outputs from the microcontroller are fed in two 555 timers implementing a push-pull configuration in order to provide higher gain in the signal transmission.

The microcontroller is able to generate pulses of 3.3 V, resulting in two square waves of 3.3 V peak-to-peak (pk-pk) and +1.15 V offset. A coupled output from the 555 timers, supplied by 12.0 V results in a square wave 24.0 V pk-pk.

2.4   Receiver Module

The received signal, from the ultrasonic transducer, is first limited in amplitude by an unbiased dual diode clipping circuit. Since the power of the signal decreases with distance, in order to compare different signals with different amplitudes, we want them to be limited to the same value. For an unbiased dual diode clipper the cut off occurs at ±0.7 V in both the positive and negative half of the cycle (view Figure 2-6), thus everything above +0.7 V or below -0.7 V will be cut out.

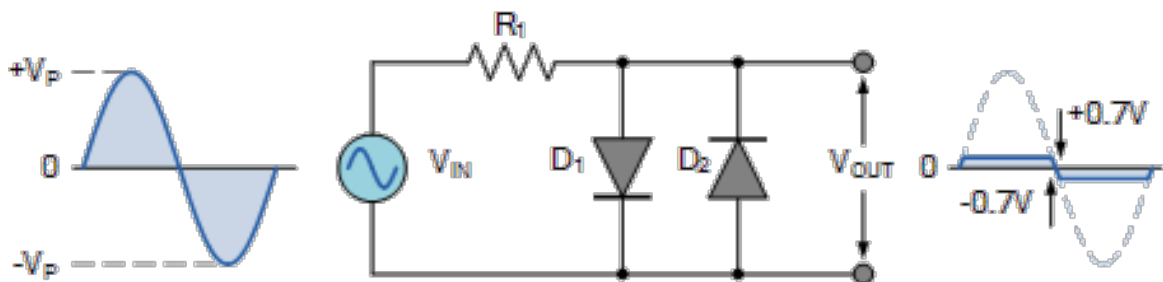*Figure 2-6 Dual Diode Unbiased Clipping Circuit (15)*

Once the signal has been reduced to a standard value, one stage of amplification occurs through an LF351 op-amp configured in single supply mode (view Figure 2-8). Low power signals need, in fact, to be amplified if they don't reach a preset threshold, required for subsequent analysis.
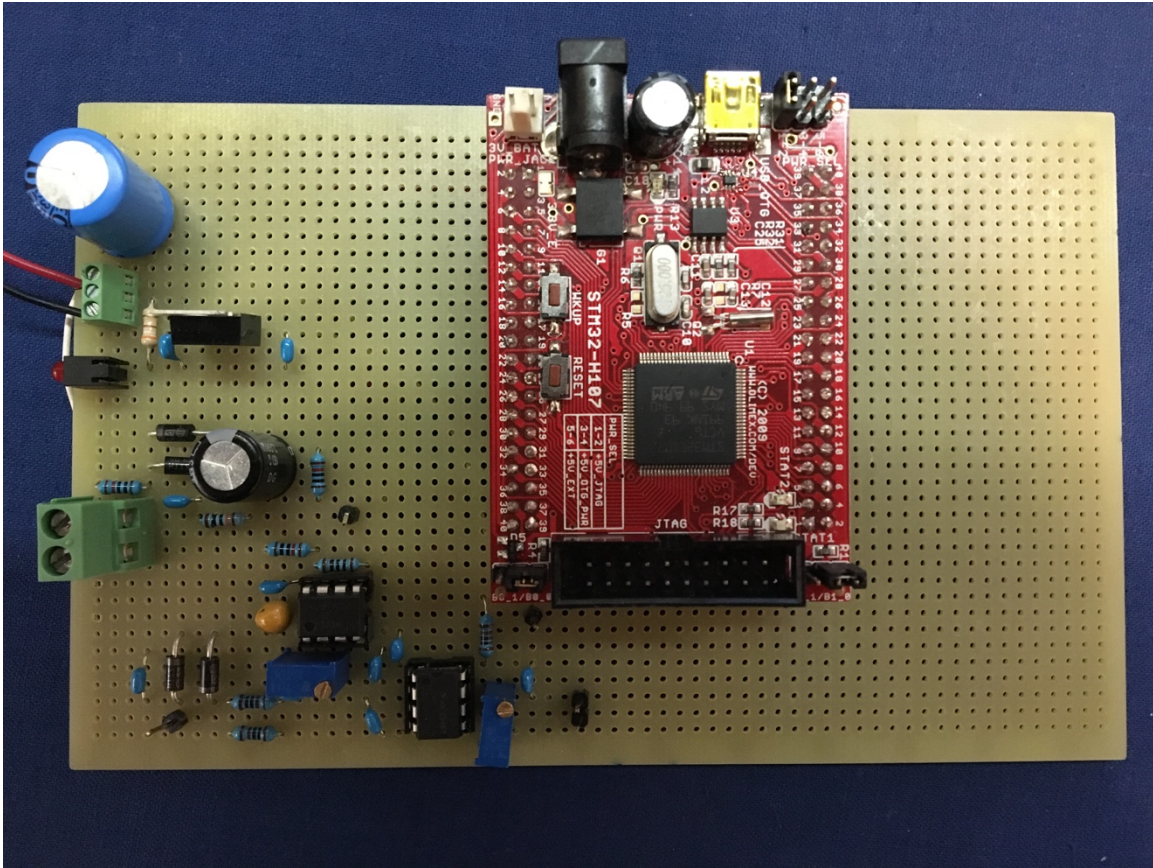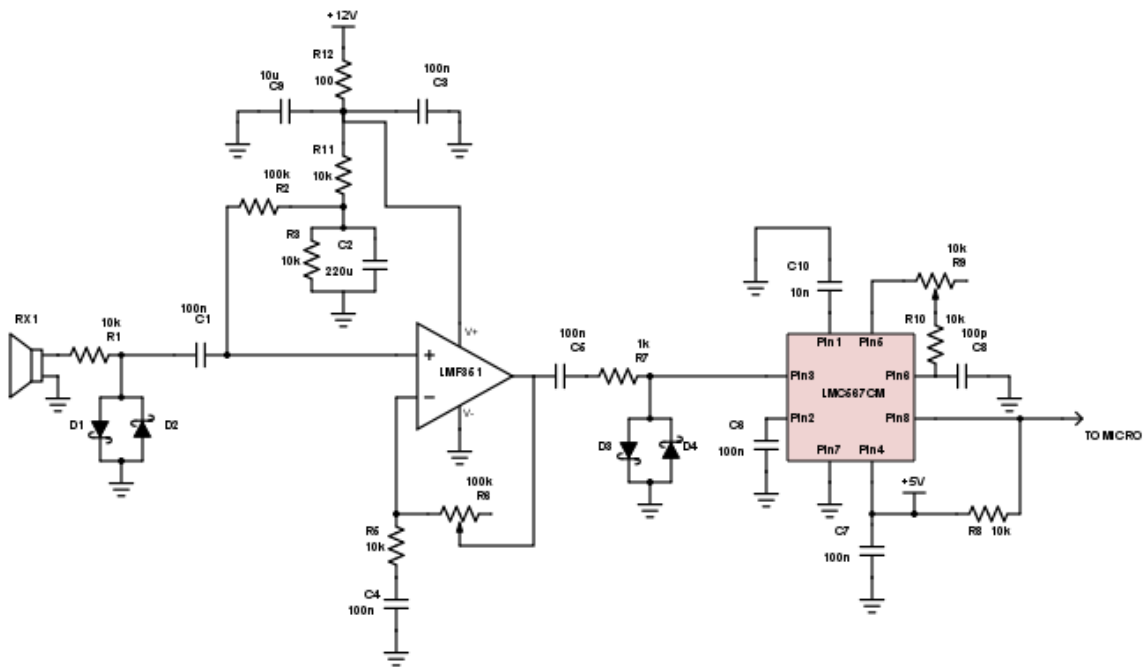
Figure 2-7 Receiver Module

Figure 2-8 Receiver Diagram

After the signals has gained enough voltage, a new stage of clipping is required to realign the signal with the standard value.

Coupling capacitors are used between the stages to keep a null DC component.

At this point the signal, still unfiltered, should resemble a square wave with 1.4 V pk-pk and 0 V offset.

As previously said, the TOF computation is performed comparing the precise time of when the signal has been received with the reference clock. The LMC567 tone decoder, once set-up accordingly, activates a switch to ground whenever its input signal falls within a properly tuned frequency bandwidth and its amplitude exceeds a preset threshold. This fast switch determines a clear mark of when the signal gets locked in or released.

A general purpose pin on a second STM32-H107 board is configured as input, and reads the state of the output pin (pin 8) of the LMC567.

Once programmed correctly, the Microcontroller will be able to extract the TOF comparing the timing with the reference GPS clock.

This set up, differs from what, most of the times, happens identifying a received signal in other examples in literature.

TELIAMADE, for example, is another ultrasound positioning system. The signal reception, though, is performed using a quadrature digital detector. The received signal from the ultrasonic transducer is amplified and filtered. The conditioned analog signal is then sampled and stored in a memory buffer. The signal sampling is done using the ADC (Analog to Digital Converter) with 10-bit resolution for a suitable dynamic range. TELIAMADE, because of its distinction of being an indoor positioning system, is hard wired with a computer, thus, the high computing power required for the ADC and the quadrature detector analysis won't be an issue (16).

In this system, light weights and small sizes are crucial. The power necessary to perform such onerous and time dependent calculations would require machines too big and heavy. In order to minimize the load of the microcontroller, then, most of the job has been shifted to the analog circuit (view Figure 2-9)
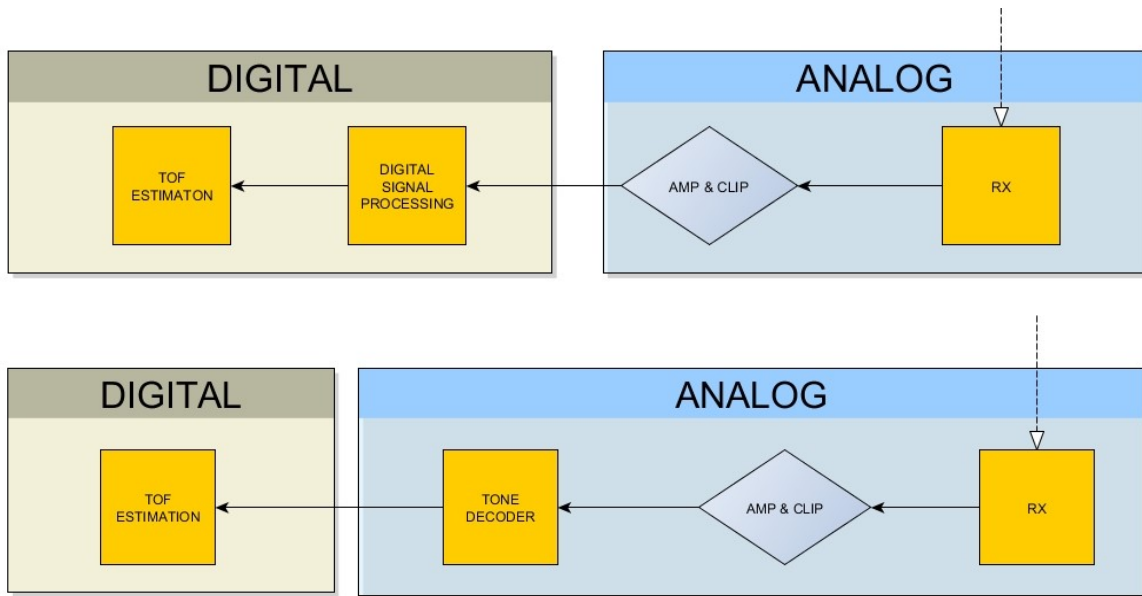
Figure 2-9 Analog vs. Digital Detection

CHAPTER 3 - TESTING

Once the design has been established and prototype circuits have been assembled, a good amount of tests are performed in order to evaluate the accuracy of the system in distance measurement. Although these results are eligible to show the fine performance of the system, it is also true that they do not actually reflect the positioning accuracy in a real environment. Before testing the whole system, we test both modules independently, in order to get a fine tune of both the transmitter and the receiver.

3.1 Transmitter Module Testing

Testing the transmitter means verifying that the output wave will resemble the one simulated with circuit analysis.

3.1.1 Output without and with Load

In order to check the output voltage, we set up the Microcontroller to generate a continuous stream of pulses at 40 kHz and we supply the circuit with 12.0 V.

The test shows how the open-end output reflects theoretical values (view Figure 3-1**Error! Reference source not found.**). Furthermore, the presence of the load (the ultrasonic transducer), doesn't reduce significantly the output voltage (view Figure 3-2).
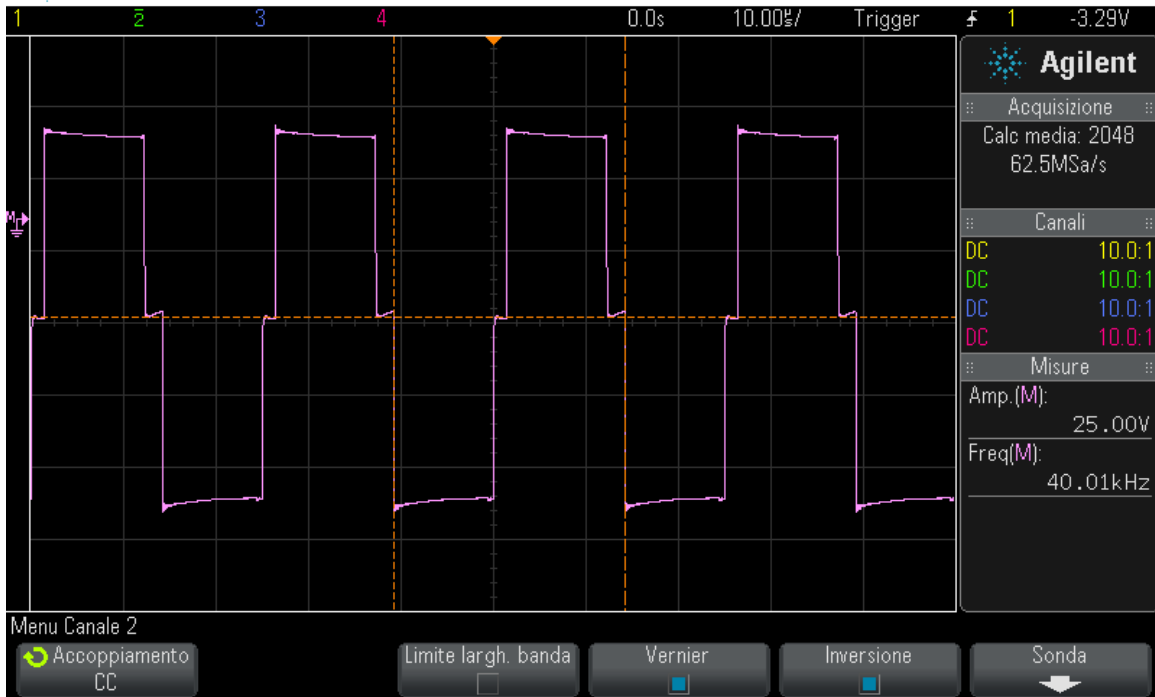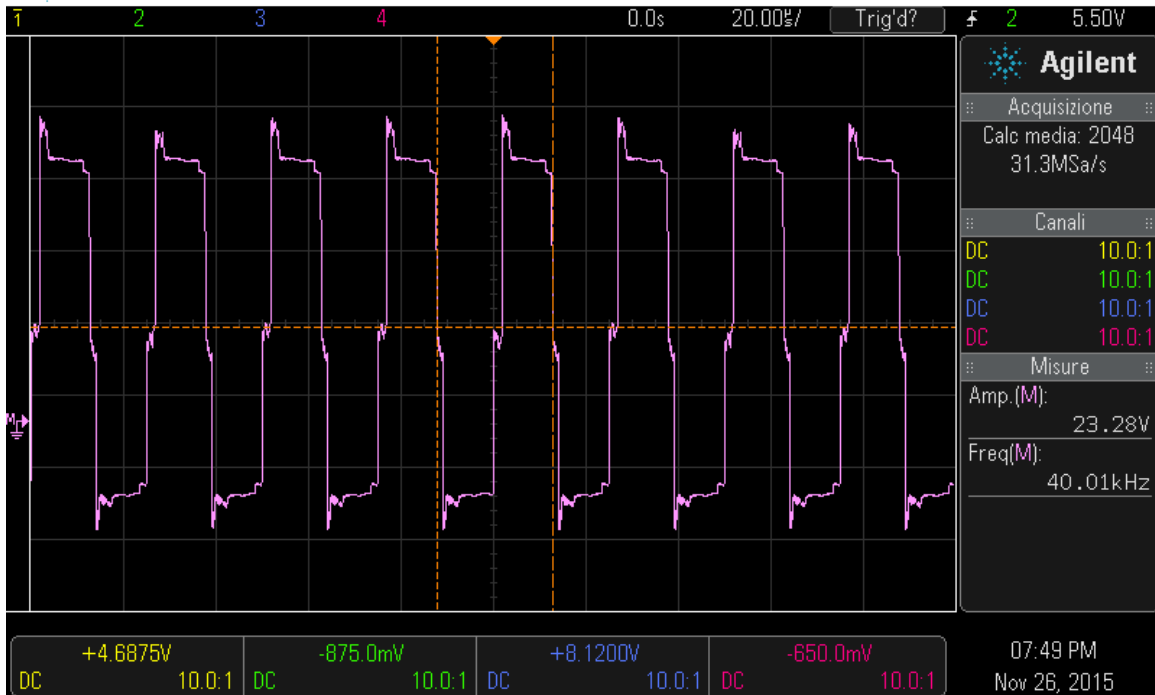
Figure 3-1 Transmitter open-end output

Figure 3-2 Transmitter output with load

3.2   Receiver Module Testing

Since more stages form the receiver module, a greater number of tests is required in order to check and tune its functionality.

3.2.1   Input Wave Shape

First of all, is necessary to characterize the input of the module. As many factor influence transmission, propagation and reception, a simple setup has been put together in order to be sure that the signal gets transmitted and received (hardware faults excluded) and to quantify the magnitude of noise and interferences.

In a quite environment (appliances known to cause interferences are switched off), the ultrasonic transducers are bonded to a stick, aligned, faced to each other and spaced 60 cm. Power is applied and a 40 kHz continuous wave is generated. The ultrasonic receiver is not connected to the module yet, and both its pins are probed (view Figure 3-3).

We obtain a sinusoidal wave, with frequency of 40kHz, a small mean value and a vague 700mV pk-pk.

Acquiring both the transmitted and the received signal, we can see, as expected, a significant delay (1620-2220 microseconds) between the begins of each, even if it's quite tricky to evaluate where the true beginning of the received signal is, since it has a not negligible rising time (view Figure 3-4).
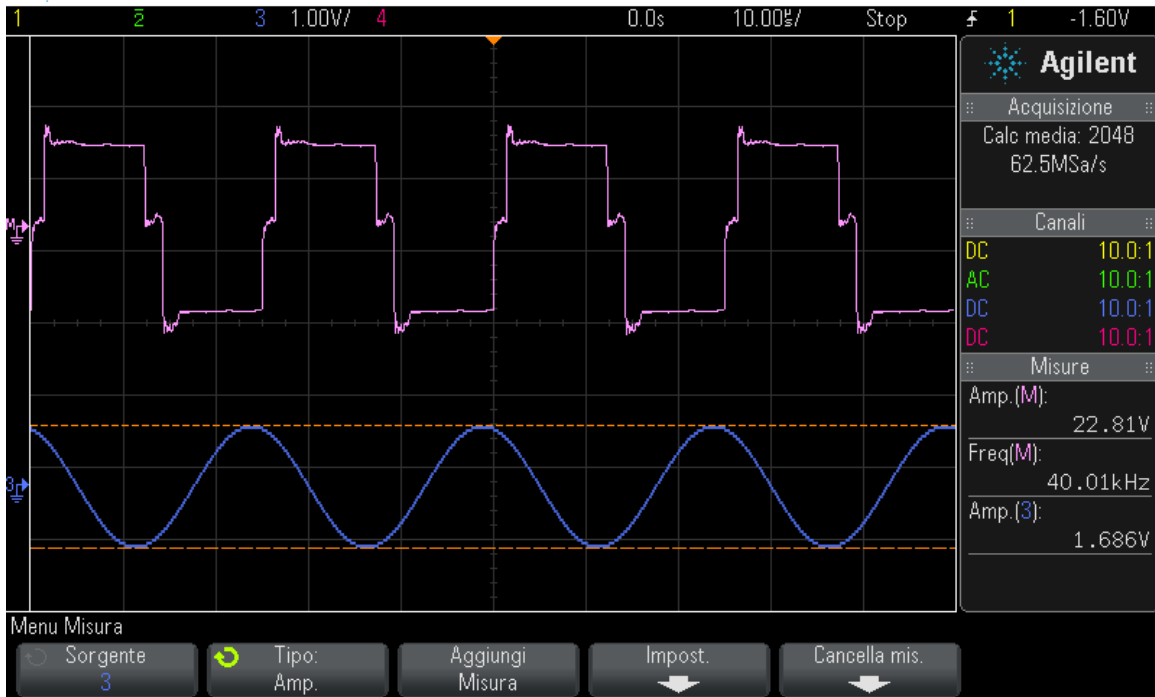
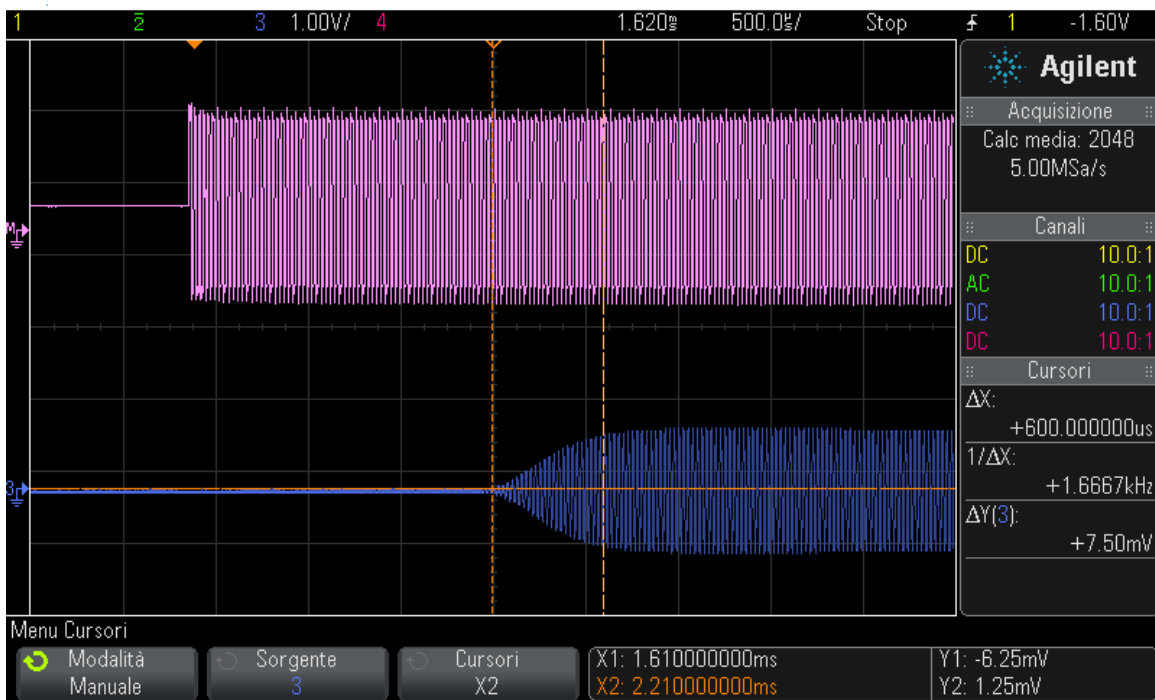*Figure 3-3 Transmitted (purple) and Received (blue) Wave Shapes.*

Figure 3-4 Transmitted (purple) and Received (blue) signals compared. Delay ~ 1620-2220 us

3.2.2 *Amplification and Normalization Coherence Test*

As said (view 2.4), before feeding the signal into the tone decoder, becomes necessary normalizing it, in order to make it "readable" the same way, weather it was strong or weak. Moreover, too weak signals (below normalization value) need to be amplified, before clipping.

Test results help us to properly adjust the gain of the op-amp.

Firstly, we want to see how clippers and amplifier stages modify signals with different intensities. We supply both the transmitter and the receiver with 12V, we set up the amplifier gain at 3 and we clamp the probe tips after the first and the second clipping stage. Starting with the transducers 200mm away, we check the oscilloscope while increasing the distance between the nodes. When they are still pretty close to each other, e.g. 250mm (view Figure 3-5), the first clipping stage kicks in to limit the signal and what happens in the other stages is considered negligible, since they just amplify and re-limit the signal to the same value. This strategy avoids to saturate the op-amp if the input voltage gets too high.

Taking the transducers more distant, e.g. 600mm (view Figure 3-6), the amplitude of the received signal decreases to a value below the clipping point, then it gets amplified by 3 times going over the ±0.7V threshold and then normalized, ready to be fed into the TD.

Going even further, e.g. 1300mm (view Figure 3-7), the signal intensity get so low, that even after the amplification, it stays below the clipping point. This is an undesired situation, in fact, the amplitude of the signal might not be enough to trigger the TD, failing to estimate the TOF.
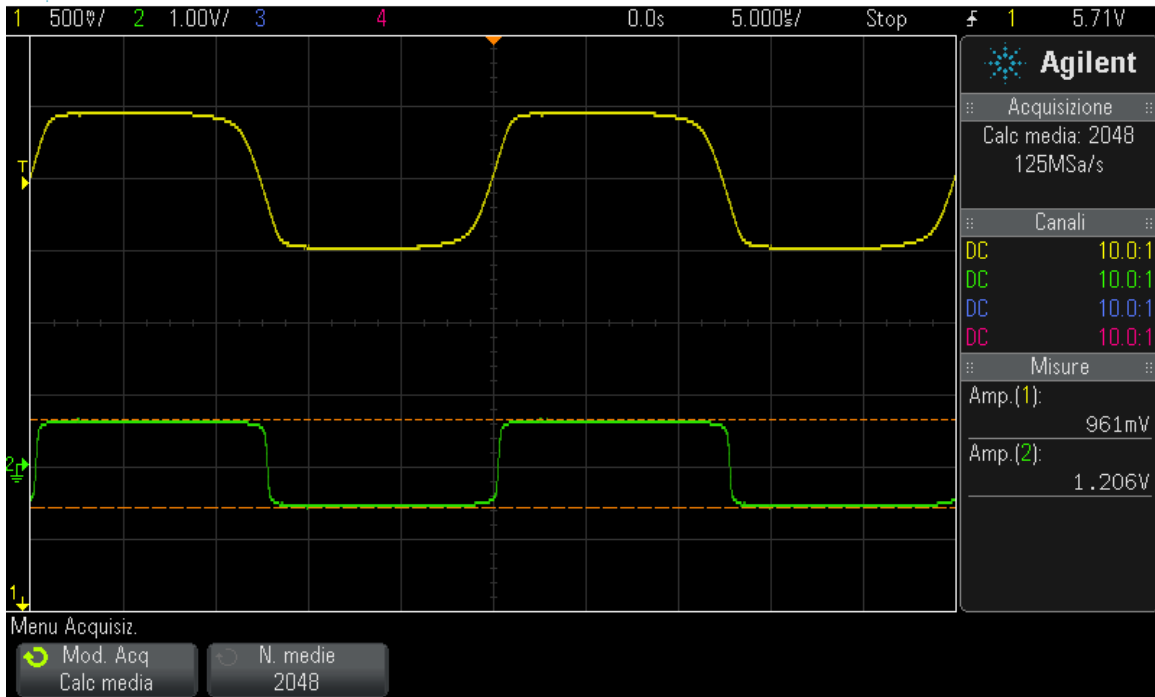
Figure 3-5 250mm input signal. After the 1st clipper (yellow) and after the 2nd clipper (green).
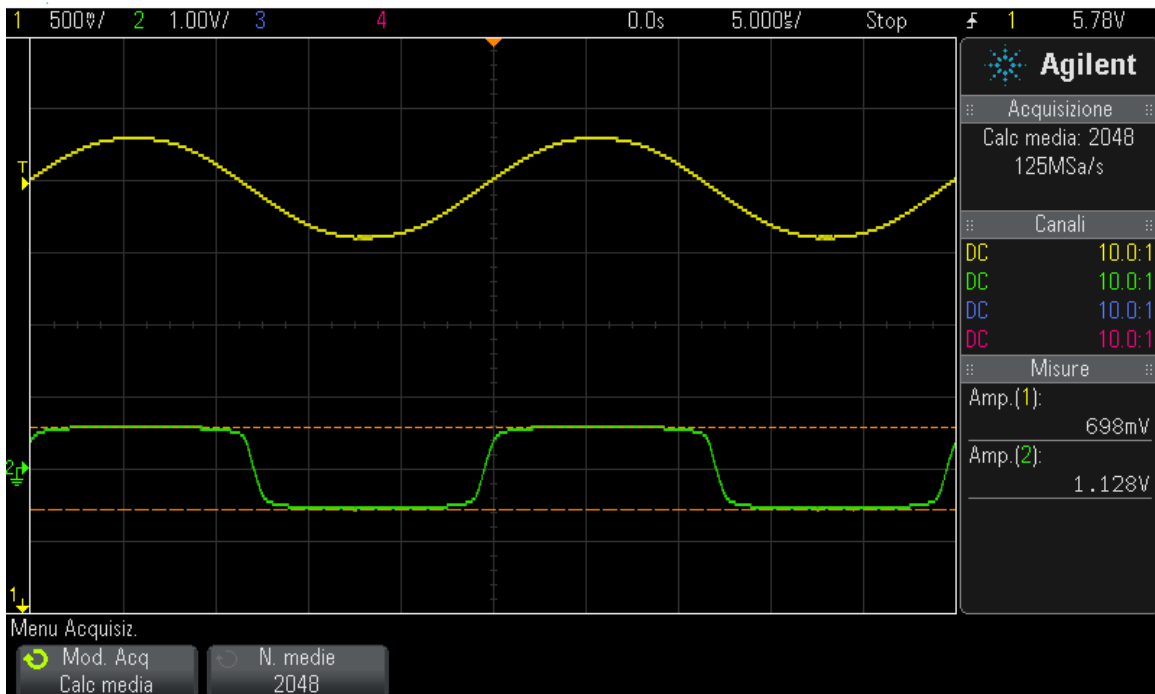
Figure 3-6 600mm. After the 1st clipper (yellow) and after the 2nd clipper (green).
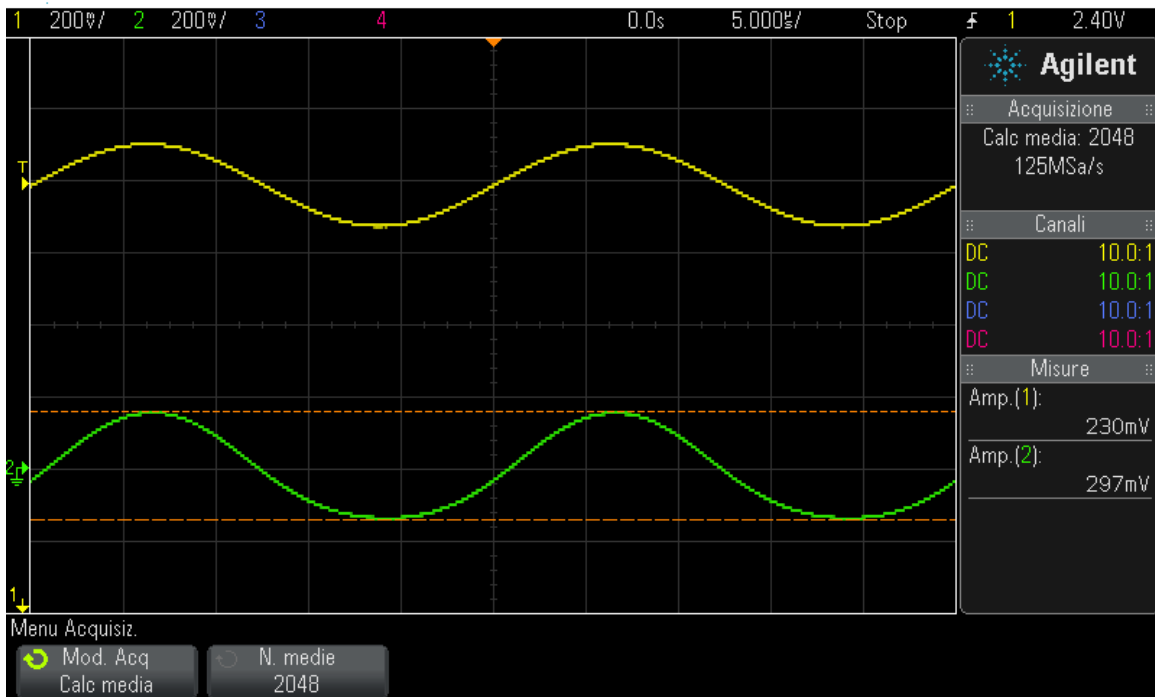
Figure 3-7 1300mm. After the 1st clipper (yellow) and after the 2nd clipper (green).

3.2.3 Estimation of Gain Upper Limit

In order to compute higher TOF, so, we should boost up the op-amp gain.

However, all the charts illustrated by now, to make them clear, come from the oscilloscope set to display just average values. It doesn't show how noise get involved in the process.

Increasing the gain in unrestrained way, at some point, will let the TD to be triggered improperly by noise. This is clearly an undesired situation, that must be handled, setting an upper limit to the gain factor.

To estimate this maximum value, we proceeded setting up the nodes at a distance far enough to rule out any possible proximity effect, but not that much the intensity might get too low. With the same settings as for the previous test, we collocate the transducers 1000mm far from each other, then we increase the gain step by step, until estimations are overrun by invalid results. Therefore, we are testing system availability, varying the gain factor.

The statistics gathered from the test are shown in Table 3:

Gain Factor	Valid Measures
3	100.0 %
9	100.0 %
15	99.8 %
20	98.7 %
23	95.4 %
25	83.0 %
27	74.3 %
30	35.2 %

Table 3 System Availability and Gain Factor

When the noise falls in the TD bandwidth and gets amplified above the pre-set threshold, it triggers the TD earlier than the hunted signal would do. Usually, more than 90% of the time, this happens as soon as the microcontroller start listening on the incoming port, giving a result, that is such far from a reasonable one, it can be filtered out with a simple C-script. However, sometimes this happens in close immediacy with the signal, making it tricky to rule it out. This led the user to be pretty conservative when setting up the gain for the op-amp, therefore, it's been decided not to test the system beyond a 20 gain factor.

3.2.4   Noise Suppression System

In order to prevent the system to give false readings, because of noise TD triggering, a feature has been added. Since the signal has a preset duration, the Microcontroller has been instructed to discard results that don't give a TD lock in window of the same width of the pulse sequence. Re-evaluating the gain upper limit, if we compare, just the percentage of false readings, ignoring valid and discarded results, we get a better situation that can let us pushing the gain limit a further away (view Table 4), possibly up to a 25 factor.

Gain Factor	Invalid Measures	Invalid Measures with NSS
3	0.0%	0.0 %
9	0.0%	0.0 %
15	0.2 %	0.1 %
20	1.3 %	0.2 %
23	4.6 %	1.0 %
25	17 %	1.5 %
27	25.7 %	3.2 %
30	64.8 %	8.4 %

Table 4 Invalid Measures: standard vs NSS

3.2.5   Tone Decoder: Test and Tune

The Tone Decoder should be set up properly to recognize when the desired signal gets received. As said, it should have a narrow bandwidth, and a fast switch, but configuring it to have the best of them at the same time, is not viable.

Once trimmed to oscillate at twice the centered frequency, bandwidth can be regulated, changing the value of a capacitor, accordingly with the data sheet.

However, the specification concerning acquisition time delay says that for small values of C2, the PLL will have a fast acquisition time and the pull-in range will be set by the built in VCO frequency stops, which also determine the largest detection bandwidth (LDBW). Increasing C2 results in improved noise immunity at the expense of acquisition time (view Figure 3-8).

Data dispersion for acquisition time determines inaccuracies in TOF estimation. We tested it with different values of C2 and the error associated with TD acquisition time is still acceptable, especially for long TOF.

Noise instead, as already discussed, might lead to more serious issues and even if it should stay confined, limiting the op-amp gain, it's still better off to set the TD to the narrowest pass band possible.

Bandwidth as a Function of C2

Figure 3-8 Influence of C2 on Bandwidth
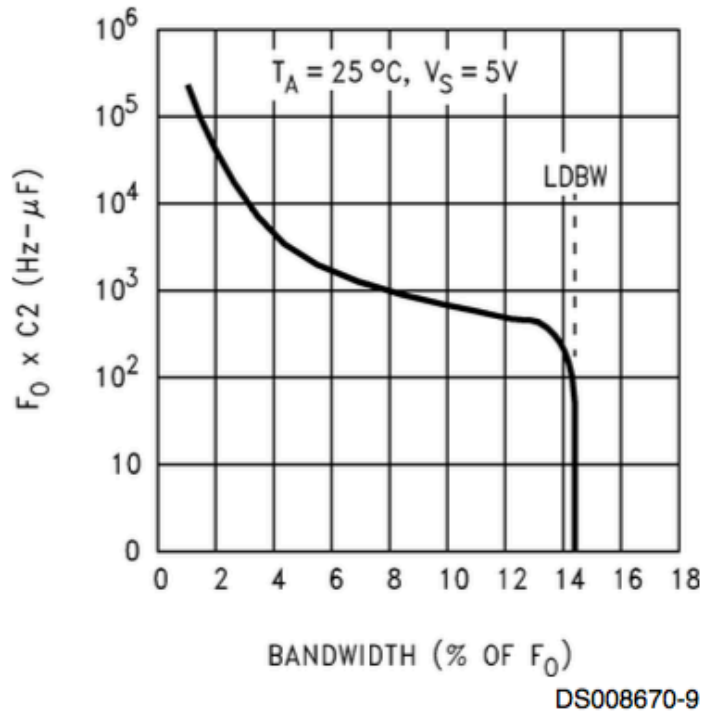
3.3 Techniques for TOF estimation

Now that the whole system has been properly configured, techniques to evaluate TOF are discussed.

3.3.1 Sequence Begin - Tone Decoder Locks In

The first and most immediate configuration, would compare the reference time with the instant when the TD locks into the signal (view Figure 3-9).
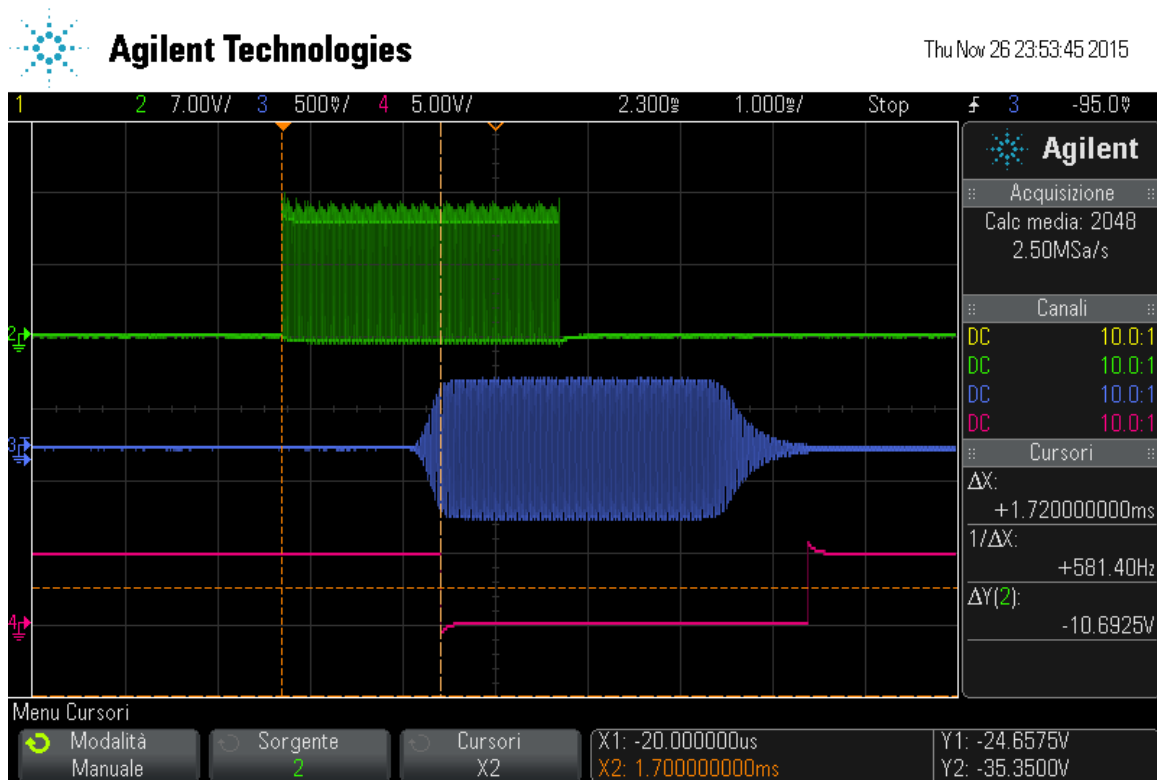
Figure 3-9 Sequence Begins - Tone decoder locks in

The test has been executed for different distances to measure giving the results shown in Table 5.

Distance (mm)	Expected TOF (us)	Average TOF (us)	Standard Deviation (us)
100	290	622	261
200	581	906	320
400	1161	1545	304
800	2323	2804	294
1200	3484	3923	336
2000	5807	702	301

Table 5 TOF Estimation: Sequence Begin - TD locks in. T=22 °C, c=344.384 m/s, Vs_tx=12 V

Although average data can be valid enough, standard deviation of data make this configuration too inaccurate to be eligible.

The combined capacitance of the whole system, in fact, produces a delay effect, due to the time needed for the circuit to be charged by the incoming signal (view Figure 3-10). This time, depends upon many factors that influence signal intensity and propagation, thus every slight change in the environment condition will affect the TOF.
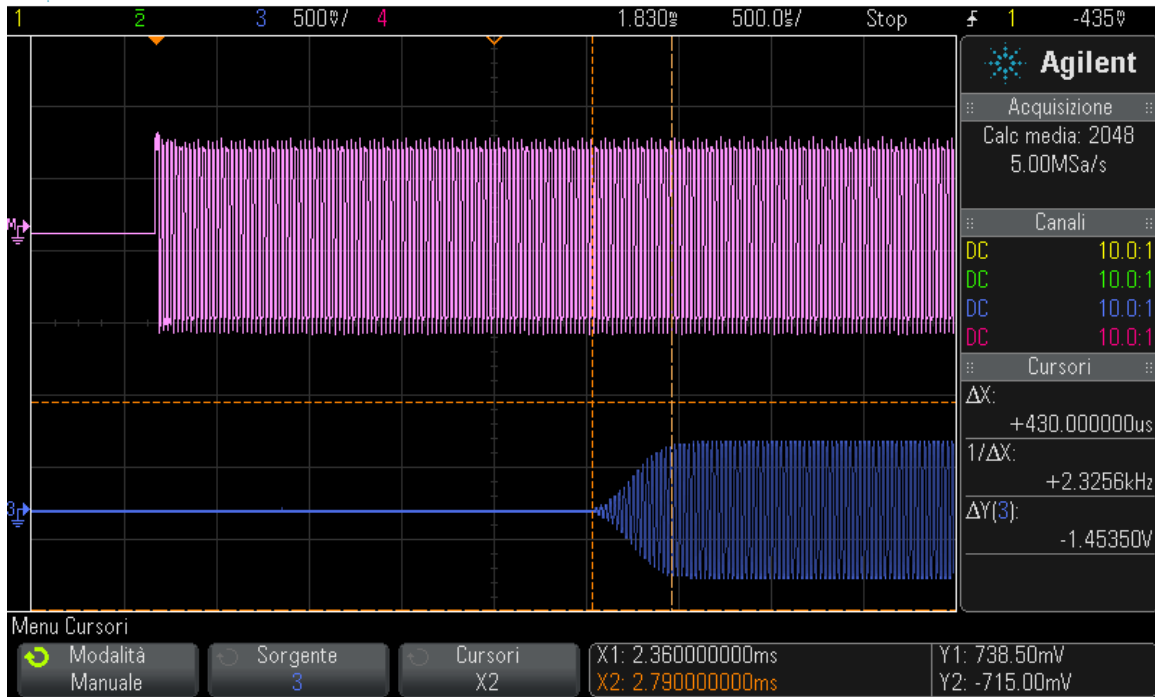
Figure 3-10 Charging Delay

3.3.2 Sequence End - Tone Decoder Releases

An alternative to avoid the error caused by the charging delay at the beginning of the signal, is to evaluate the TOA at the end of the pulse sequence (view). Since the signal has been properly clipped, the discharge of the circuit should follow a known exponential pattern. Data are collected for the same distances as for the previous test and compared (view Table 6).

With this setup, is definitely smaller.

Distance (mm)	Expected TOF (us)	TOF Average (us)	TOF Standard Deviation
100	290	2081	233
200	581	2243	185
400	1161	2420	109
800	2323	3002	41
1200	3484	4128	19
2000	5807	6852	16

Table 6: TOF Estimation: Sequence end - TD releases. T=22 °C, c=344.384 m/s, Vs_txm=12 V

In order to simulate different amplitude for the received signals, we repeat the same test with a different power supply for the transmission module (view   Table 7).

Distance (Voltage) mm (Volts)	Expected TOF (us)	TOF Average (us)	TOF Standard Deviation
100 (12)	290	2081	233
100 (6)	//	1401	82
200 (12)	581	2243	185
200(6)	//	1481	70
400 (12)	1161	2420	109
400 (6)	//	2043	63
800 (12)	2323	3002	41
800 (6)	//	3044	33
1200 (12)	3484	4128	19
1200 (6)	//	4122	18
2000 (12)	5807	6852	16
2000 (6)	//	6851	16

Table 7: Sequence end – TD releases. Influence of TXM Voltage Supply

As expected, most results don't seems affected much by the power of the transmission. However, a slight variance is still present largely due to a not ideal clipping, still sensible to the signal amplitude.

For close measurement, instead, the dependence of the TOA from the transmission power is even more emphasized than the TOA measured at the beginning of the signal. This has been

assessed to be related to a mechanical inertia of the sensor, that tends to keep on oscillating even when is not energized anymore. This phenomenon, continues to transmit a signal, even if the amplitude is significantly lower, and thus false data when the transducers are close enough (view Figure 3-11).
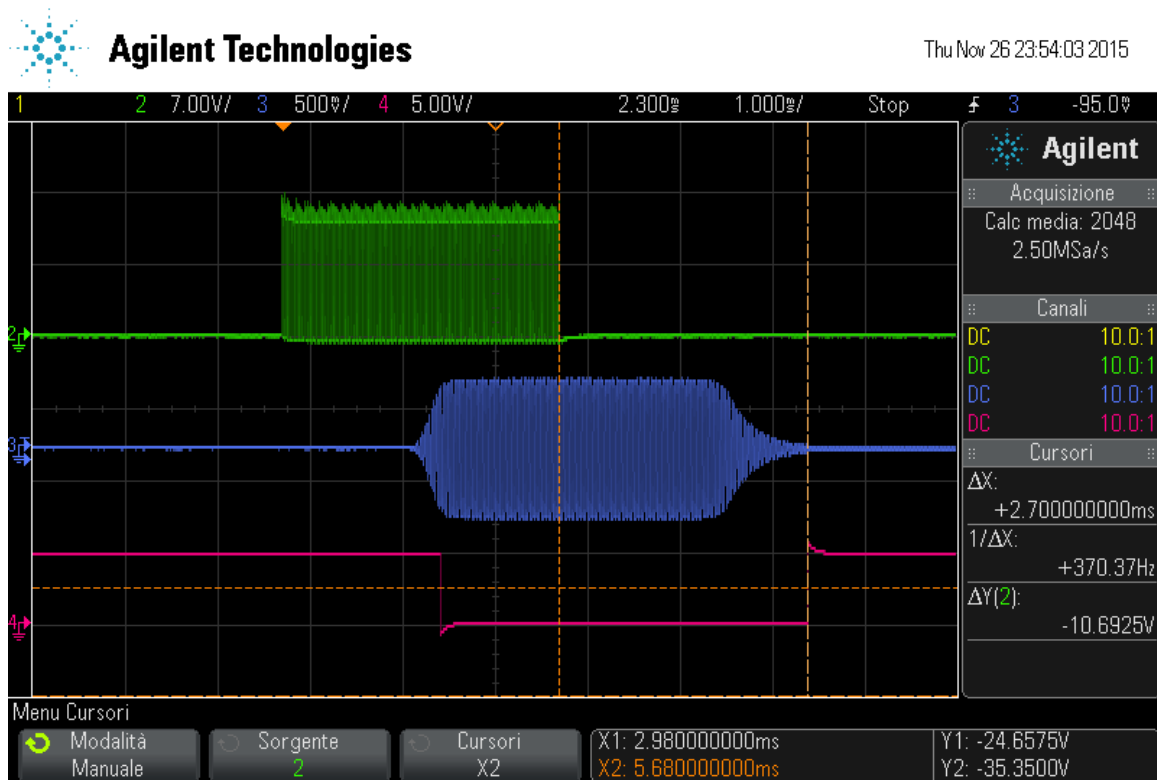
Figure 3-11

3.3.3 *Forced Frequency Switch-Up (FFSU)*

In order to prevent mechanical inertia to produce false readings for small distances, has been implemented a technique, that force the TX to oscillate at a higher frequency, as soon as the standard pulse has been completed (view Figure 3-12). This frequency jump, should be high enough to ensure that the TD releases the locked signal, or rather that the oscillation frequency falls beyond both the TD's and the transducer's bandwidth.

The updated system has been tested and results (view Table 8) are satisfactory, thus fixing this major issue for close measurement.

Distance (Voltage) mm (Volts)	Expected TOF (us)	Average TOF (us)	Standard Deviation TOF (us)
100 (12)	290	1204	24
100 (6)	//	1212	20
200 (12)	581	1507	20
200(6)	//	1513	18
400 (12)	1161	2136	16
400 (6)	//	2141	16
800 (12)	2323	3262	15
800 (6)	//	3264	15
1200 (12)	3484	4391	15
1200 (6)	//	4390	15
2000 (12)	5807	6803	15
2000 (6)	//	6803	15

Table 8: TOF Estimation: FFSU. Influence of TXM Voltage Supply

Figure 3-12 TOF with FFSU
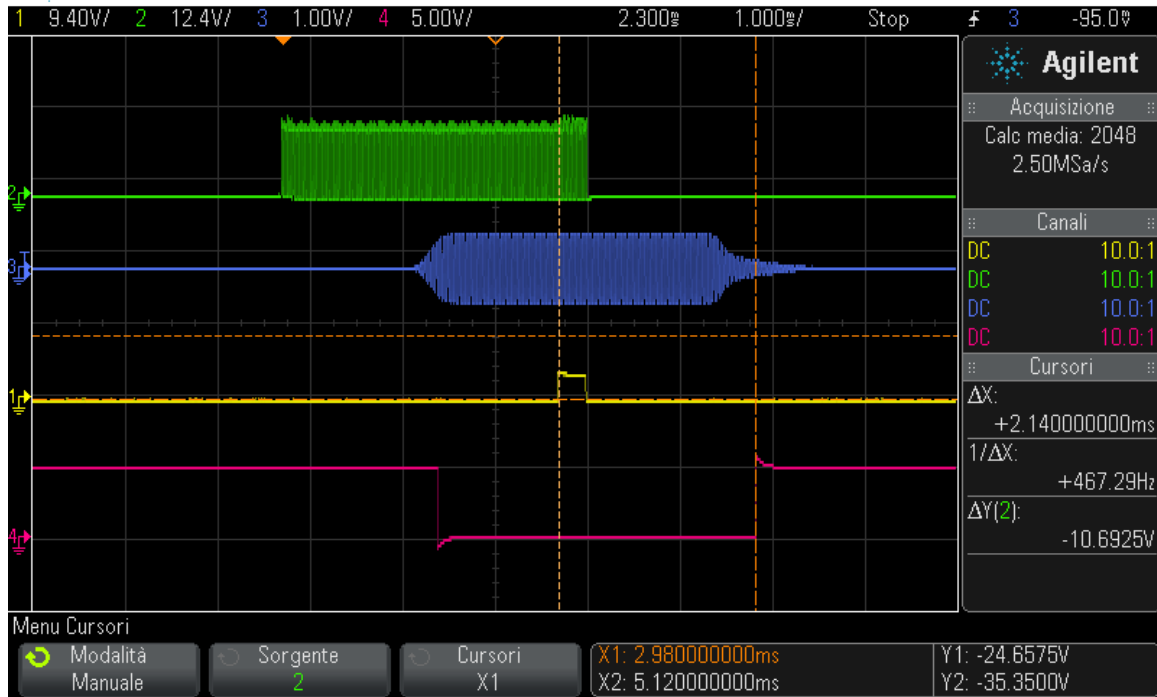
Following a graph, shows how normal distributions mute when FFSU is active, for short distances (Figure 3-13).
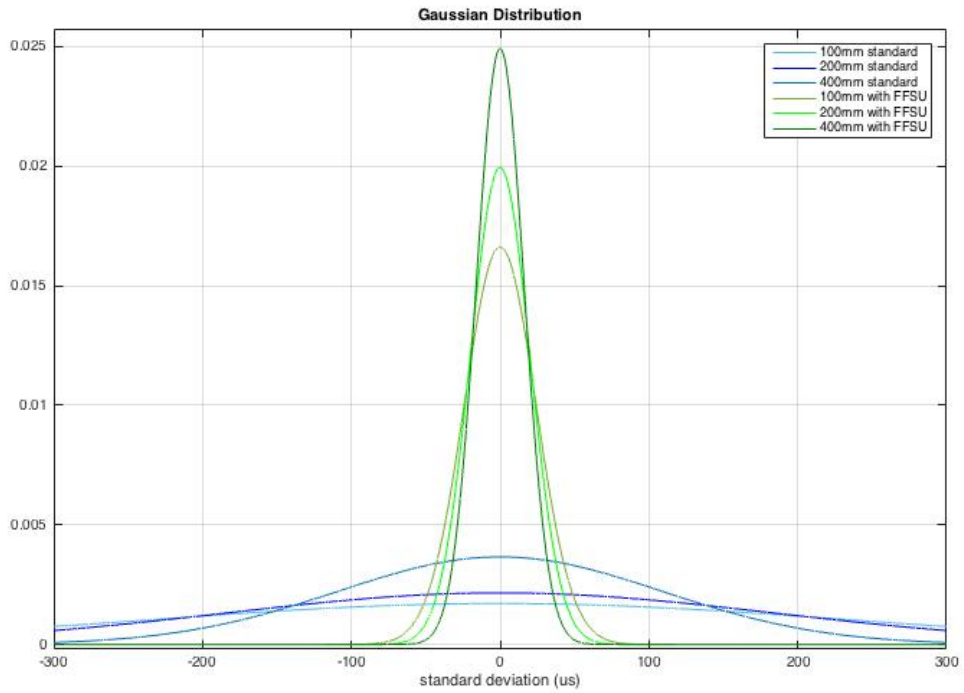

Figure 3-13 Graphical Comparison between standard and FFSU results for close distances. Gaussian distributions. x-Axis in microseconds
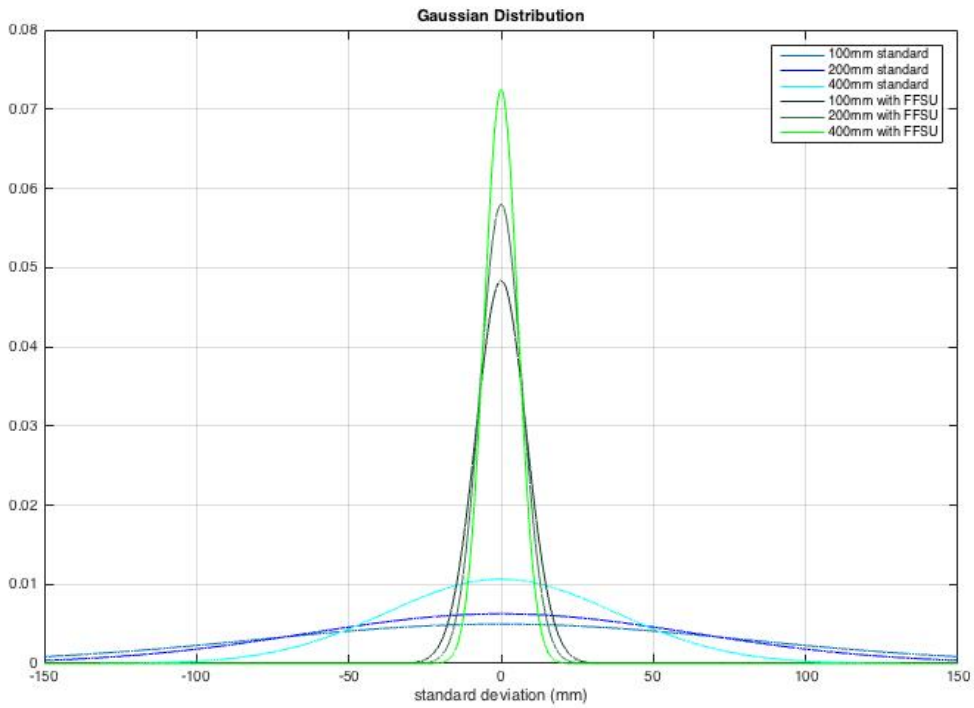

Figure 3-14 Graphical Comparison between standard and FFSU results for close distances. Gaussian distributions. x-Axis in millimeters

3.4 System Range Test

Getting an accurate measure, is just one of the most important aspect, regarding the implementation of this system for UAV formation flight. Reaching enough range, in fact, is essential to make it profitable. Testing the system requires the RXM gain factor to be set at the maximum rated value (see 3.2.3), and progressively increasing the distance between the nodes. The assessment has been performed for different values of the TXM supply voltage (view Table 9).

Distance (mm)	Valid Data (%)	Valid Data with NSS (%)
2000	100 %	100 %
3000	100 %	100 %
4000	97 %	100 %
5000	94 %	99 %
6000	83 %	96%
7000	62 %	84 %
7500	49 %	69 %
8000	-	59 %
8300	-	48 %
8500	-	39 %

Table 9: Avilability: Comparison between standard system and NSS

As distance increases, getting no-data become more and more frequent. Beyond a 50% of valid communications the test has been terminated.

The highest power supply value of 16V is stemmed by the 555 timer recommended operating conditions [cit. datasheet]. This provides a maximum reliable range of 7 meters, augmentable to 8 meters with NSS.

3.5 Calibration

Computed TOF and actual TOF don't match and the error depends upon different factors. The most relevant cause derives from the delay of internal components. This is very steady and with small variance, thus, it can be easily cut out. However, standard deviation due to others disturb is not controllable, thus a linear regression (view Figure 3-14) is applied in order to calibrate the measure apparatus.
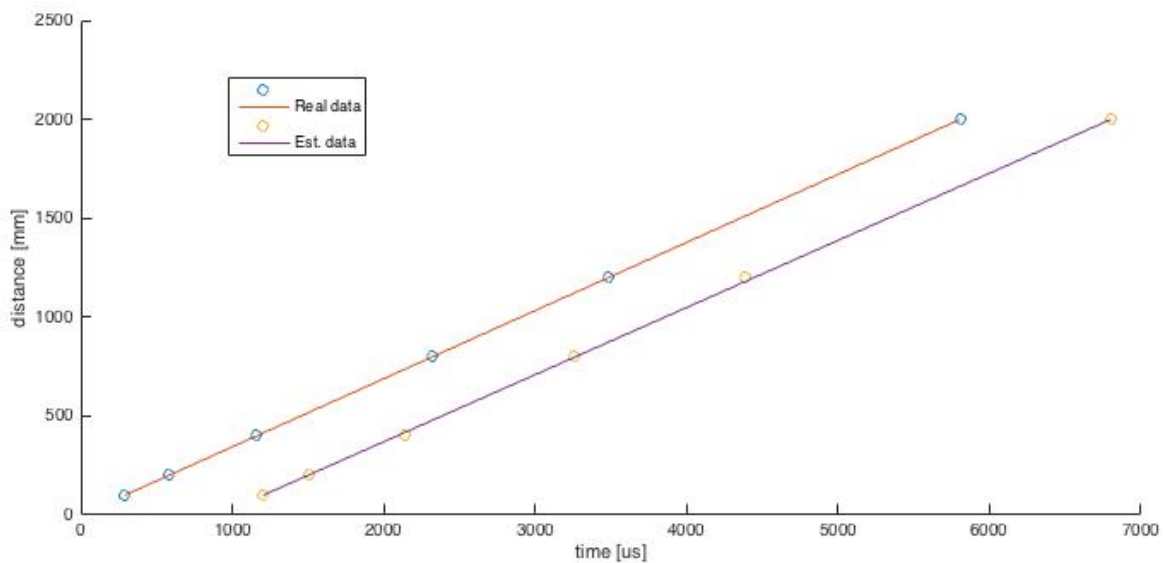

Figure 3-15 System Calibration. Linear Regression

As we can see from the graph, the most significant error is due to a fixed delay of internal components and it can be estimated in 920 microseconds. Once correction is applied, we obtain the following table (view Table 10).

Expected Distance (mm)	Expected TOF (us)	Estimated TOF (us)	Avg. Estimated Distance (mm)
100	290	284	98
200	581	587	202
400	1161	1216	419
800	2323	2342	807
1200	3484	3471	1195
2000	5807	5883	2026

Table 10: Calibrated Device. Distances Expected vs. Extimated

3.6   Limitations

Although the system can provide pretty accurate measures, it suffers of different limitations that must be addressed before the appliance must be suitable for its purpose.

3.6.1   Short range

As already tested at 3.4, the range is still too restricted to provide the coverage necessary for the envisaged use. This is due to the limited power that can be supplied to the timers. In order to increase the range, the TXM should be re-designed in order to provide higher transmission power. The transducers, in fact, can be energized with a voltage up to 30Vrms that should be adequate to provide a range of about 15 meters.

Although this solution might be feasible, when the aircraft are further away than the maximum range of the device, accuracy become less and less important. The required precision at this point can be so low, that a pure GPS positioning system might carry out the job by itself. It is suggested, before attempting to increase the range of the device, to analyze more deeply a US-GPS collaborative solution.

3.6.2   Narrow Beam Angle

As for the majority of the ultrasonic transducers, beam angles higher than 50°-60° gives an attenuation larger than -6dB (view Figure 3-16), too weak to be relied on.

To accomplish the planned mission, is necessary to design a system that would make possible measures with a wider angle range. These solutions might be, mounting the sensors on a moving platform or using multiple sensors to cover a bigger span.
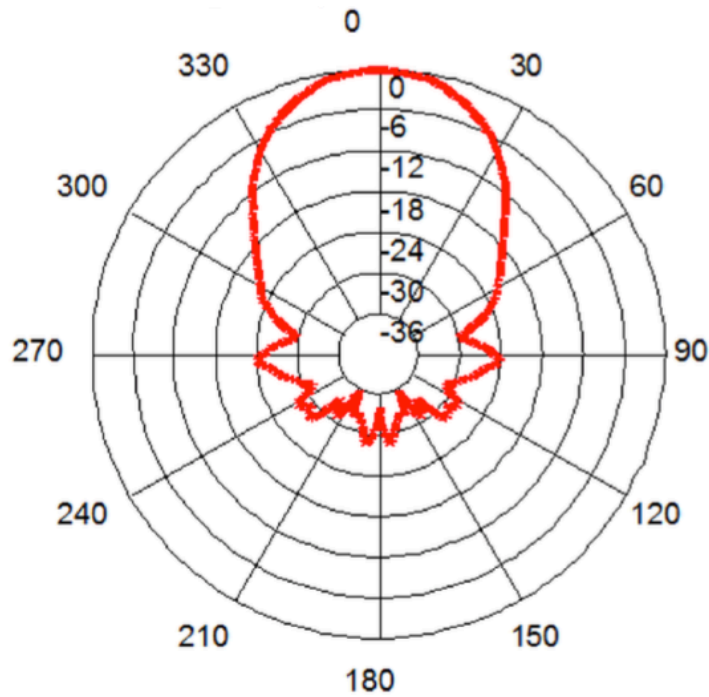

Figure 3-16 Ultrasonic Transducer Beam Angle

CHAPTER 4 - CONCLUSIONS AND FUTURE DEVELOPMENTS

The present research has proposed a promising solution for a formation flight instrument to be mounted on small UAVs. The entitled device, at this stage of development, have accomplished just few of the requirements needed for its implementation as a UAV formation flight instrument. It can provide measures with good accuracy and reliability and it has a compact size and a low power required. However, the short range achievable and the narrow beam angle, cannot provide enough coverage, demanding for improvements. Furthermore, noise is still not negligible and just one pair of nodes can't provide 3-D positioning.

Future developments should first address the issue of small coverage; some solutions have already been proposed at 3.6, but their design has not been attempted yet.

Secondarily, noise is still affecting the results, in fact, the filtering effect of the TD is not enough to guarantee a great noise immunity, thus the necessity for a proper active/passive pass-band filter and/or a modulation in the carrier signal.

Accuracy, moreover, is still too dependent by the capacitance of the RXM that would make the TD trigger to misbehave. Both noise and capacitance issues, related to the TD improper triggering, might lead us in the future to substitute the TD with a DSP system (i.e. digital quadrature detector), even if programming complexity would substantially increase.

Once the system has been upgraded to a more accurate, reliable and capable one it should be tested in the operative environment. Temperature correction has already been assessed but since ultrasonic waves travel at the speed of sound, the effect due to the air speed of the UAVs might, as well, influence the data. Moreover, other onboard systems might cause not negligible interferences, i.e. engine and propeller.

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