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SAR SYSTEM DEVELOPMENT FOR UAV MULTICOPTER PLATFORMS

A Degree Thesis

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Abstract

This thesis describes the optimization of a synthetic aperture radar (SAR) at X-band and its integration into an unmanned aerial vehicle (UAV) of type octocopter.

For such optimization the SAR system functionality was extended from singlepol to fulpol and it has been optimized at hardware level in order to improve its quality against noise figure. After its integration into the octocopter platform, its features has been used in order to be able to make preprogrammed routes and to perform fully autonomous apertures. Motion compensation techniques have been studied also for processing higher quality images by the analysis of inertial data from the platform and the phase story of points of the image during the aperture.

The UAV model used it's the Spreading Wings S1000 made by the manufacturer Dji and the SAR system it's the ARBRES-X developed by the UPC.

Resum

Aquesta tesi descriu l'optimització d'un radar d'obertura sintètica (SAR) en banda X i la seva integració en un vehicle aeri no tripulat (UAV) de tipus octocópter.

Per a aquesta optimització s'ha estès la seva funcionalitat de singlepol a fulpol i s'ha optimitzat a nivell de hardware per millorar la seva qualitat a nivell de soroll. Després de la seva integració a la plataforma octocópter s'han aprofitat les seves funcionalitats perquè pugui realitzar vols prepogramats i realitzar obertures de manera completament autònoma. També s'han estudiat tècniques de compensació de moviment per poder processar imatges de major qualitat mitjançant l'anàlisi de dades inercials de la plataforma i la història de fase de punts de la imatge durant l'apertura.

El model de UAV utilitzat és el Spreading Wings S1000 del fabricant DJI, i el sistema SAR és el ARBRES-X desenvolupat per la UPC.

Resumen

Esta tesis describe la optimización de un radar de apertura sintética (SAR) en banda X y su integración en un vehículo aéreo no tripulado (UAV) de tipo octocóptero.

Para dicha optimización se ha extendido su funcionalidad de singlepol a fulpol y se ha optimizado a nivel de hardware para mejorar su calidad a nivel de ruido. Tras su integración en la plataforma octocóptero se han aprovechado sus funcionalidades para que pueda realizar vuelos prepogramados y realizar aperturas de manera completamente autónoma. También se han estudiado técnicas de compensación de movimiento para poder procesar imágenes de mayor calidad mediante el análisis de datos inerciales de la plataforma y la historia de fase de puntos de la imagen durante la apertura.

El modelo de UAV utilizado es el Spreading Wings S1000 del fabricante Dji, y el sistema SAR es el ARBRES-X desarrollado por la UPC.

To all the people I met and accompanied me during the course of this adventure, inside and outside the university

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1. Introduction

1.1. Objectives and motivation

The project is carried out at the Signal Theory and Communications department (TSC), specifically at the Remote Sensing Laboratory, located in the Escola Tècnica Superior d'Enginyeria de Telecomunicacions de Barcelona (ETSETB), which pertains to the Universitat Politècnica de Catalunya (UPC).

The purpose of this project is to efficiently integrate a SAR system in a multicopter platform and take profit from its advantages. This project corresponds to an early prototype test.

The main objectives set in this project are:

- Understand the concept of SAR systems and be able to comprehend its whole performance, from hardware to software levels.
- Fully integrate a SAR system over an UAV octocopter platform in order to be able to make apertures in flight.
- Make the platform able to operate autonomously by using preprogramed routes and automatic triggering of the SAR system.
- Build a gimbal stabilizer to compensate the movement in the pitch axis of the antennas during the acquisitions.
- Study the application of motion compensation algorithms in order to improve the processed images.
- First studies of feasibility to implement multipass interferometry.

This project started from the Phd thesis made by René Acevo Herrera "*Sistemas de teledetección activos y pasivos embarcados en sistemas aéreos no tripulados para la monitorización de la tierra*" [1]. In this work the ARBRES-X SAR system was mounted on a RC (radio controlled) plane and interferometric single pass measures were made. Also it's based on the thesis proposal made by Marc Lort Cuenca "*Multidimesional SAR for earth observation*" [8].

The main initial ideas were provided by the supervisor Albert Aguasca and the PhD student Marc Lort Cuenca. The focalization algorithms used for obtaining images were developed by the PhD student Marc Lort Cuenca.

1.2. Work plan

Project: SAR system development for UAV multicopter platforms	WP ref: WP1
Major constituent: Planning and research	Sheet 1 of 5
Short description: Study about the SAR systems and get familiarized with both hardware and software	Real start date: 17/02/2015 Real end date: 06/03/2015

related to the project, to start planning the entire project.	Start event: End event:	
Internal task T1: bibliographic research. Internal task T2: familiarization with the arbres system and the UAV platform. Internal task T3: project plan proposal.	Deliverables: Project plan proposal	Dates: 06/03/2015

Table 1. Work package 1

Project: SAR system development for UAV multicopter platforms	WP ref: WP2	
Major constituent: Build the first hardware prototype	Sheet 2 of 5	
Short description: test the UAV platform in order to obtain its capacity, autonomy, etc. and make a first integration of the SAR system.	Real start date: 09/03/2015 Real end date: 23/03/2015	
	Start event: End event:	
Internal task T1: test the specifications of the UAV Internal task T2: test the SAR system without the platform (including antennas measuring) Internal task T3: integrate an Arduino controller for interact between both systems Internal task T4: test in flight both systems together	Deliverables:	Dates:

Table 2. Work package 2

Project: SAR system development for UAV multicopter platforms	WP ref: WP3
Major constituent: improvement of the system	Sheet 3 of 5
	Real start date:

Short description: improve the system in order to acquire inertial information and compensate the movement of the antennas by building a gimbal	Real end date:	
	Start event: 23/03/2015 End event: 27/05/2015	
Internal task T1: integrate a razor imu with an Arduino in order to obtain gps and inertial information from the platform in flight Internal task T2: integrate a gimbal system for compensating the movement of the platform (pitch axis) Internal task T3: autopilot configuration. Internal task T4: test in flight both new systems.	Deliverables: Critical review	Dates: 24/04/2015

Table 3. Work package 3

Project: SAR system development for UAV multicopter platforms	WP ref: WP2	
Major constituent: processing and applications	Sheet 4 of 5	
Short description: analyze the current processing algorythms and improve them in order to use new applications.	Real start date: 27/04/2015 Real end date: 15/06/2015	
	Start event: End event:	
Internal task T1: analyze the actual processing algorythms. Internal task T2: implement an efficient motion compensation algorithm for processing. Internal task T3: implement multipass interferometry.	Deliverables:	Dates:

Table 4. Work package 4

Project: SAR system development for UAV multicopter platforms	WP ref: WP2	
Major constituent: final report	Sheet 5 of 5	
Short description: write and present the final report of the project	Real start date: 15/06/2015 Real end date: 10/07/2015	
	Start event: End event:	
Internal task T1: final report delivery. Internal task T2: final project presentation.	Deliverables: Final report	Dates:

Table 5. Work package 5

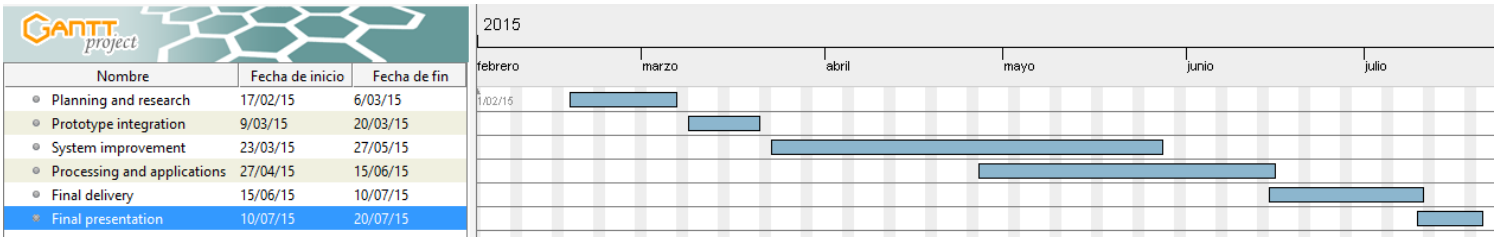

Figure 1. Gant diagram

1.3. Incidences

The first prototype of the system (single pol images and without preprogramed routes) worked successfully. But during the improvement of the system a lot of problems were faced such as the second channel of the acquisition card, used for taking Full Polarimetric (fulpol) images. It was not working due to a damaged connector. Another problem was inside one of the low noise amplifiers (LNA) introduced as the first element of the reception chain. A lot of time was invested in order to fix the problems that were discovered, as it was unknown if it was a hardware or software problem. During the search of solutions, some others failures were faced, such as the burning of three different solid state drives due to a bad voltage supply.

Also an Arduino controller responsible of making the trigger of the SAR system broke down during a measurement campaign, which delayed the planned data for acquiring images. For the development of the gimbal, several inertial units were tested until it was able to work properly.

These incidences took more time to repair than expected, leading to not allowing to investigate as much compensation algorithms as initially expected.

2. State of the art of the technology used or applied in this thesis:

2.1. Introduction to Synthetic Aperture Radar

Radars (RAdio Detection And Ranging) are systems that use electromagnetic waves to determinate range, altitude, speed or direction of objects, without having direct contact with it (telemetry). The antenna of the radar transmits pulses of microwaves and the received signal is stored and processed.

SAR systems use less directive antennas than other type of radars the SAR system moves while it acquires data, creating the effect of having an array of antennas, and resulting in a higher directivity to generate high resolution images. In summary, a SAR system it's a radar device capable of providing images of high resolution.

They can be classified in three main types according to where they are mounted and its aplication:

- GBSAR (Ground Based SAR): mounted into terrestrial platforms. Used in small-to-medium scale areas
- Spaceborne SAR: mounted into satellites. Used in long scale areas. An example is the SAR system in the Magellan probe orbiting around Venus. (Figure 3)
- Airborne SAR: mounted into planes. Medium to large scale areas. (Figure 2)

Figure 3. Image of Venus taken by Magellan Spacecraft

Figure 2. NASA's AirSAR system integrated on a Douglas DC-8 plane

2.2. The ARBRES-X SAR System

The ARBRES-X (AiR Based REmote Sensing) system it's a SAR system working at X band (9'65GHz) that has been developed by the Remote Sensing Laboratory in the UPC. It works with a Stepped Linear Frequency Modulated Continuous Wave (SLFM-CW). The ARBRES-X SAR System has a power consumption of 1'98A and a total weight of less than 2kg with reduced dimensions, which makes it suitable to be integrated in small UAV's. It can be seen in Figure 4.

The SLFC-CW signal is generated by a Direct Digital Synthesizer (DDS). The receiver is composed by two low-noise chains with a direct zero IF demodulator where a sample of the transmitted signal is used as a local oscillator. The baseband signal acquisition by a commercial high speed digitizer, which supports two channels. It is controlled by a computer with a solid state drive. The whole chain can be seen in Figure 5.

The Back-Projection Algorithm (BPA) is used to process the acquired data and to obtain focused images. The received signal is range compressed applying the Fast Fourier Transform (FFT) and the BPA is applied to perform the azimuth focusing.

Figure 4. ARBRES-X SAR System

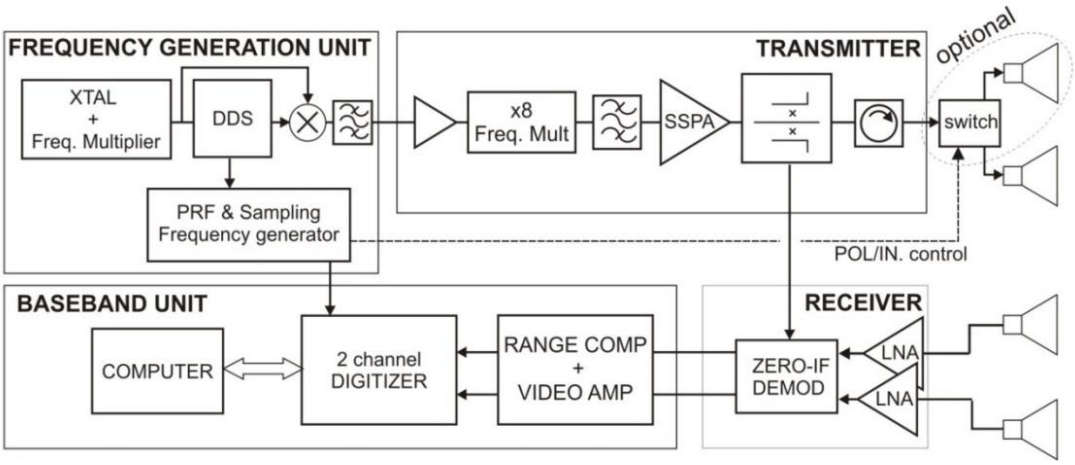

Figure 5. ARBRES-X SAR System architecture

Table 6 sumarizes the main characteristics of the system.

System Parameters	X-Band
Carrier Frequency (f0)	9'65GHz
Chirp Sampling Frequency (fs)	44'62MHz
Chirp PRF	5'44KHz
Chirp Bandwidth	100MHz
Transmitter Power	30dBm
Reciever Chain Gain	up to 70dB
Range Resolution (nominal)	1'5m
Teorethical Swath	3'75km

Table 6. ARBRES-X characteristics

The high cost that represents using aerial platforms such as planes has led to the evolution of UAV platforms. For that reason, the ARBRES-X system has been integrated in a UAV platform. [1][3][4][5][6]

When the ARBRES-X system was integrated into a Radio Controlled (RC) plane (Figure 6), it was capable of flying at high speeds (40m/s) at high altitudes keeping the platform stable. However, it had important limitations such as the lack of control of the flight trajectory.

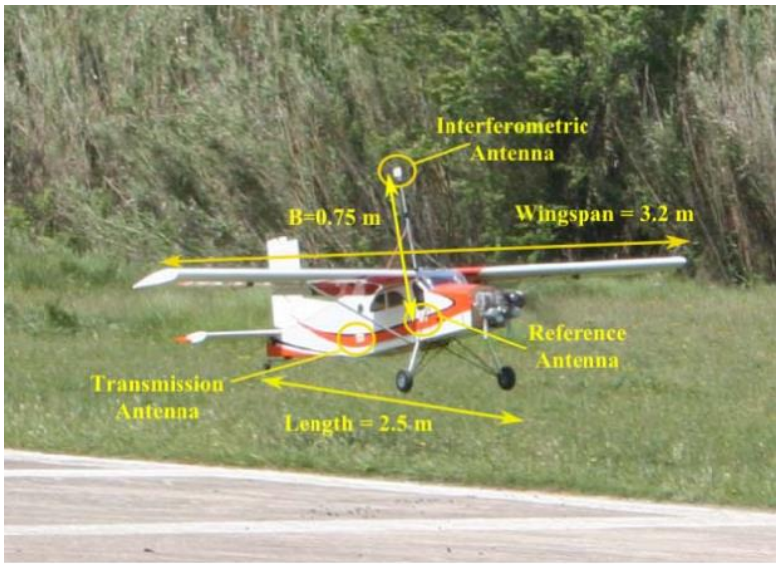

Figure 6. ARBRES-X System loaded into an RC plane

The test site selected to perform some measurement campaigns was the Real Aero Club Barcelona-Sabadell (RACBSA) Radio Control Airfield placed in Ripollet (Barcelona, Spain). This place provide us a controlled scenario with high reflectivity. (Figure 7)

Figure 7. Ripollet test site

In the results obtained in Figure 8 [6], the UAV was flying at a constant velocity of 37'6m/s and an altitude of 378 meters. In Figure 8 we can see an example of an obtained image without applying any kind of Motion Compensation (MoCo). The image obtained can be easily compared with the real image (Figure 7), especially around the main road and the

field. Two points with high reflectivity corresponding to the PARC and trihedral units can be in the field.

Figure 8. Image without MoCo

An autofocusing algorithm was developed in order to improve the resolution of the image. It basically consists in, by looking at specific bright points, looking at their phase story and comparing it with the theoretical ideal value. Then, by making some approximations we predict the phase story of the other points of the image. This algorithm was named Alabort Agorithm .

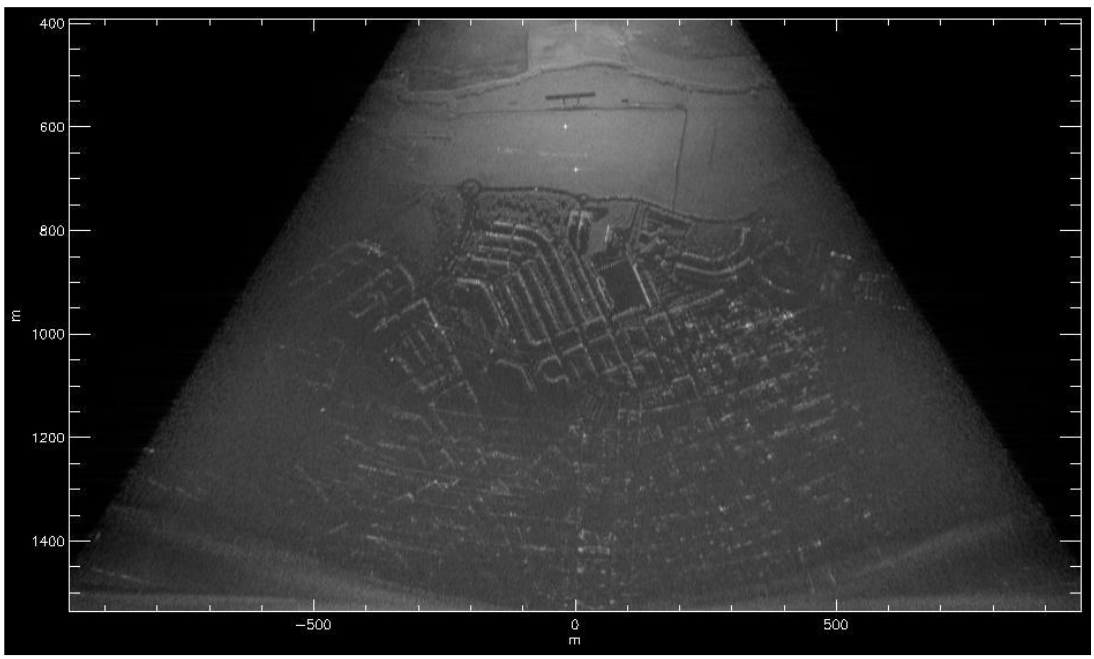

Figure 9. Image with MoCo

An improvement on the overall quality of the image can be seen. The buildings and the roads can be seen much more clearly, especially on the upper side of the image. The two prominent targets on the field have focused almost perfectly.

3. Methodology / project development:

The work developed during the implementation of the present project can be classified in three main blocks: the multicopter platform, with its configuration in both hardware and software, the SAR system and all the external devices used in order to improve the the system.

3.1. UAV multicopter platform

As it was introduced in section 2.2, mounting the ARBRES-X system into the RC plane has its advantages but also its weakness. It has a very high stability in flight but it has a complex take-off and landing, requiring a skilled pilot to control the flight and the dependency of a railway. Also the exact flight trajectory cannot be accurately controlled, and it's very complex to implement an autopilot system. That's why a multicopter platform has been chosen to board the ARBES-X SAR system.

3.1.1. DJI Spreading Wings S1000

The Dji Spreading Wings S1000 it's a commercial octocopter mainly used for aerial photography. Due to its dimensions it's possible to attach other devices. The bridges designed for a camera gimbal were recycled in order to attach the SAR system.

This platform can lift up to 11kg giving us a weight margin for our system. Its foldable design allow us to fit it easily in a car for easy transportation. With one set of batteries (3x22'2V lipo batteries) a flight time of approximately 9 minutes it's achieved, which is enough to perform a preprogrammed flight and to have a margin without reaching a critical battery level (as will be explained in 3.1.2). Another important characteristic is that it can land and take off in almost any surface.

Figure 10. Dji Spreading Wings S1000 platform

3.1.2. **A2 flight controller**

The A2 flight controller is the hardware used in order to fly and configure our platform. It comes with its own software for configuration. It's composed by the controller itself, an IMU sensor (Inertial Measurement Unit) to obtain inertial information, a gps (Global Positioning system) sensor and a status led. It comes with its own software for parameters configuration. As the controller is compatible with different flight platforms, several parameters must be configured according to our particular case, such as the type of aircraft used (octocopter in this case), the IMU orientation, and the position of the IMU and GPS according to the centre of gravity. The IMU it's at -10cm in X direction, and the GPS at -20cm in Z direction. (Figure 11)

A voltage protection was also configured in order to prevent a possible crash of the platform due to a discharge of the batteries during the flight. When the voltage decreases to 22V, a warning led starts blinking and when it decreases to 21V, the platform descends in order to prevent the crash.

It also has the option to connect a gimbal directly to the controller but in this case is not used because the required channel it's used for other function (as will be explained in 3.1.3). Two additional channels are mapped to retract the landing gear and for returning to the home point, defined as the place where the platform took off for the last time. (Figure 12)

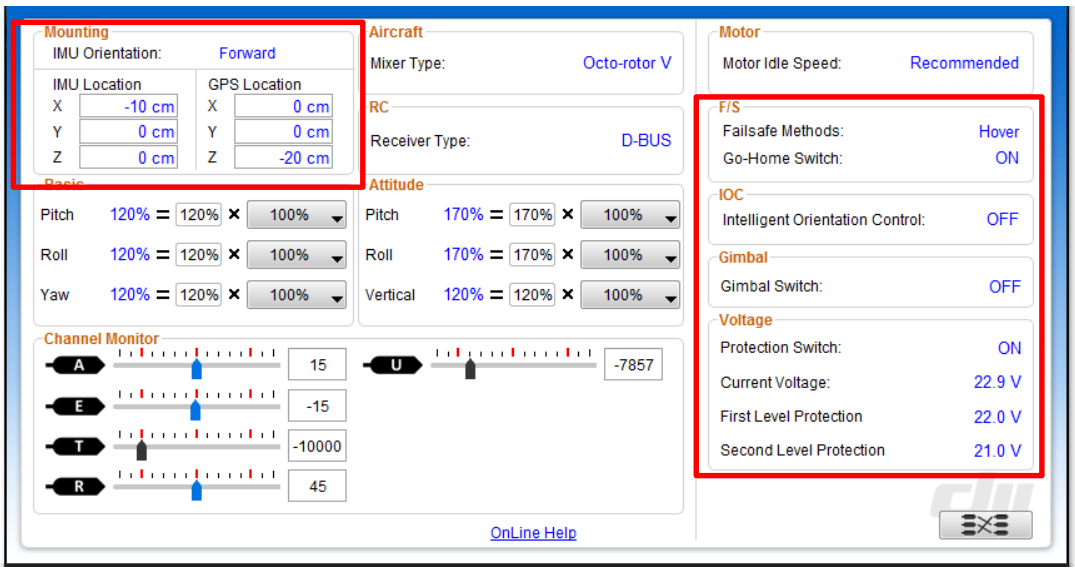

Figure 11. A2 main parameters configuration

Figure 12. A2 channels configuration

3.1.3. **Ground Station**

The DJI Ground Station system allow us to upload information to the system via wireless and to have live flight data.

The main purpose of using the Ground Station data link it's for uploading pre-programmed flight routes designed by GPS coordinates. This feature it's very important because it allows us to repeat the preprogrammed trajectory to perform an acquisition with the SAR system, wich is something important for interferometry.

The Ground Station software includes a tool for making aerial photography, the so called General Purpose Servo Action Configuration (Figure 14). In our case, this tool is used to allow us to activate the trigger to perform an acquisition with the SAR system. The trigger for the servo action uses the same port than the gimbal in the A2, so a new gimbal system was needed to be implemented (as will be explained in detail in section 3.3.2). For triggering the system, pulses of 2 miliseconds of duration (corresponding to servo position 1000) are sent during one second in order to activate the arduino trigger system (as will be explained in detail in section 3.3.1).

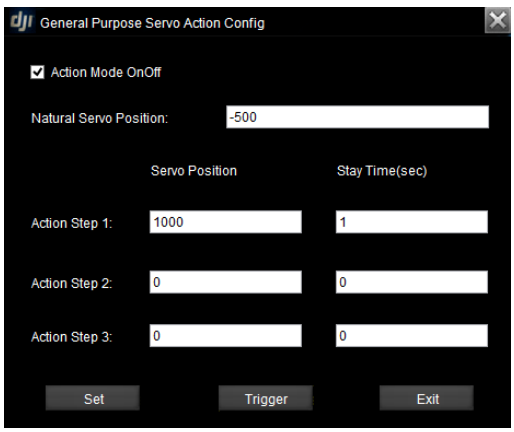

Figure 14. Servo action configuration

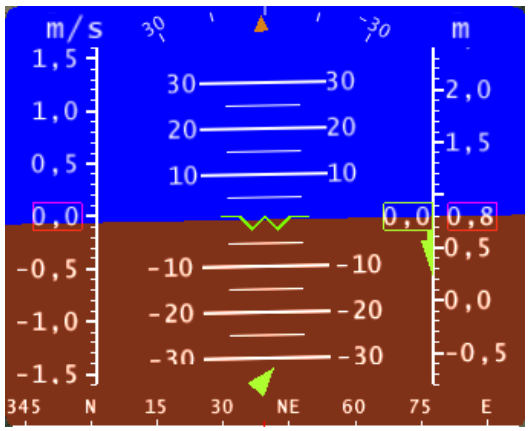

Figure 13. Ground Station telemetry data example

An example of two different preprogramed routes can be seen in Figure 15 and Figure 16, making in each one the same aperture at two different heights. For triggering the servo action, two waypoints have to be placed close to each other because the trigger it's shot in the interval of two points, and we have to make sure it doesn't shoot again once finishes

one aperture. It's easy to add more apertures at different heights by using the same coordinates just changing the height parameter. An estimated flight time it's also provided.

Something that has been extremely useful from the Ground Station software is that it gives us live telemetry data during flight (Figure 13), which allow us to see these data while doing both automatic and manual flights, allowing us to have control of the current speed and altitude.

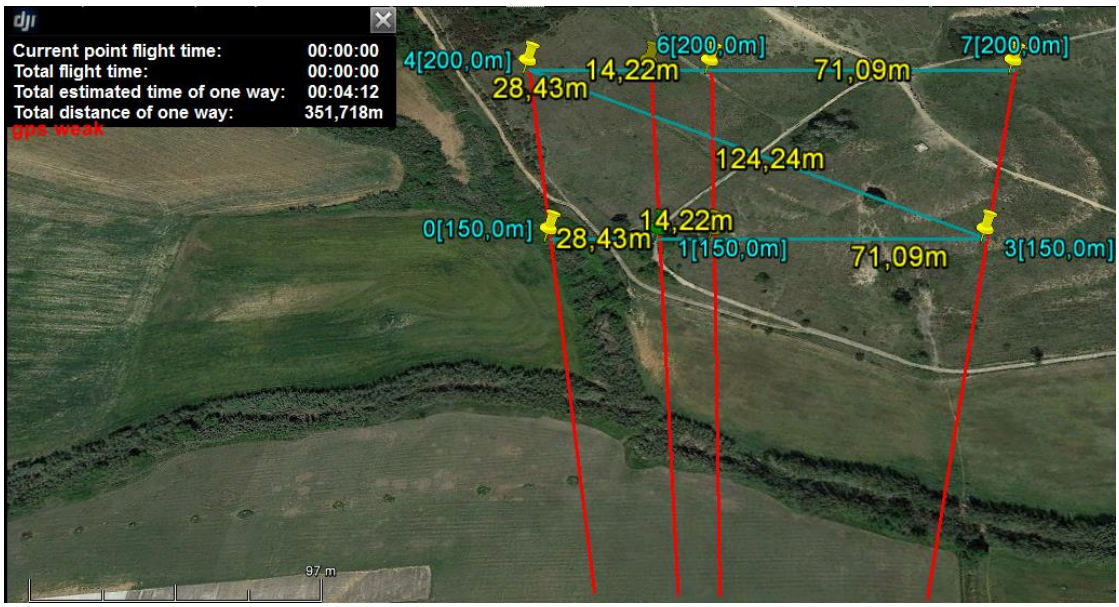

Figure 15. Short aperture. 5m/s

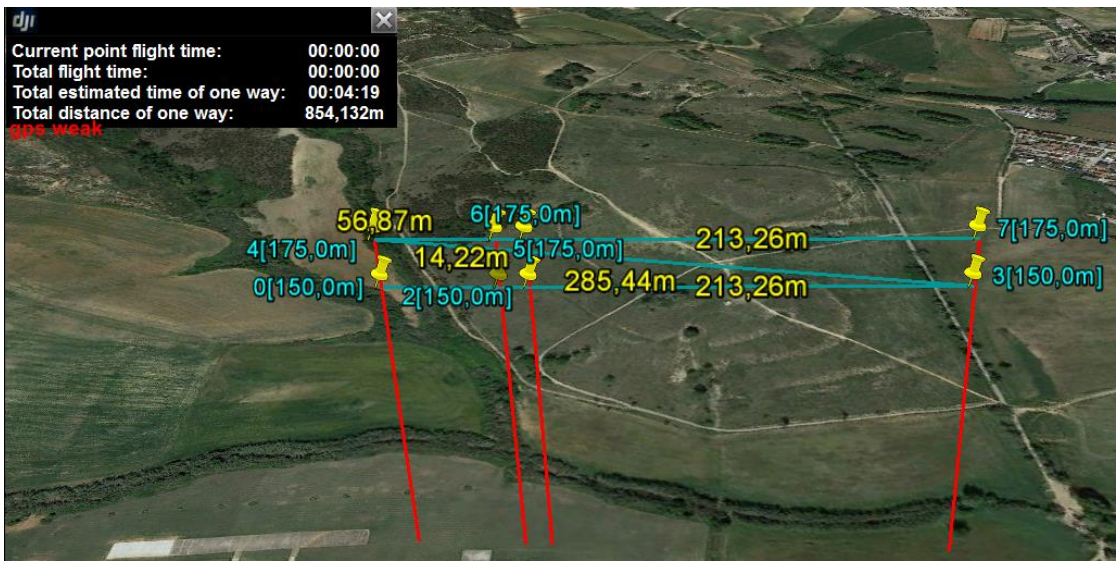

Figure 16. Long aperture. 15m/s

Something important to have into account when preprograming routes, is to give enough space to the platform to achieve the desired speed. That's a critical point because a variable velocity can affect to the quality of the focused images, as will be observed in detail in section 4.3. In Figure 15 a margin of 29 meters was set to achieve 5m/s and in Figure 16, a margin of 57 meters.

3.2. ARBRES-X SAR System hardware improvements

Different hardware improvements have been done in the ARBRES-X SAR system in order to give the fulpol capability and to improve the overall quality of the system.

3.2.1. Addition of Full Polarimetric capabilities to the ARBRES-X SAR System

In the previous version of the system, the antennas were placed directly in the fuselage of the plane. In the octocopter platform, a lightweight aluminum bar for placing the antennas was designed. The bar is 67cm long, for having enough space to ensure isolation between antennas and to be able to add all the other components, such as the low noise amplifiers (LNA) in reception with their voltage regulators and the switch board which manages the polarization control. All the components were placed in order to reduce the inertia of the bar as maximum, because when the bar is attached to the servo in the gimbal system (as will be explained in 3.3.2), it must be able to move it in a steady way. Also a tilt angle of 25 degrees to the ground in order to avoid wasting power towards the horizon. The final mount of the bar can be seen in Figure 18.

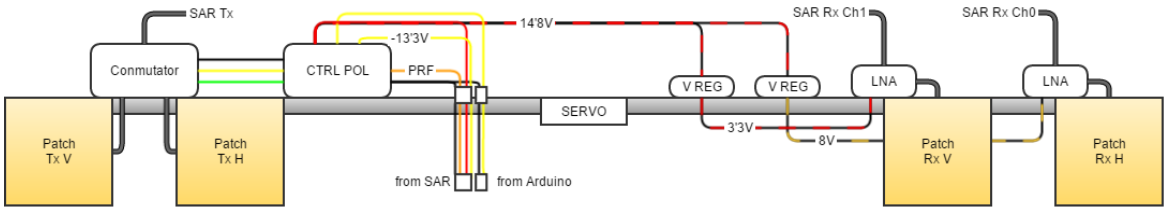

Figure 17. Antenna bar diagram

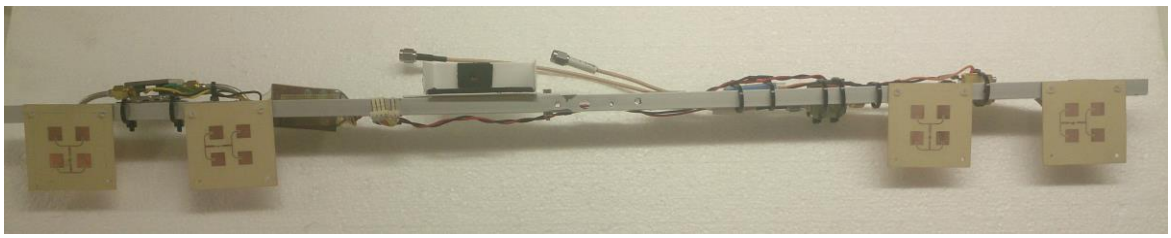

Figure 18. Assembled antenna bar

In Figure 17 can be seen the whole schematic of the antenna bar with all it's components. The PRF signal and the voltage power signals come from the ARBRES-X in a 4-pin cable. Another signal from the Arduino trigger system (3.3.1) it's also connected directly to the bar.

Patch antenna arrays were used for each polarization in transmission and reception. They are all composed by an array of four patch antenas arranged in grid. They have a separation of 50'8cm for copolar and 41'6cm for cross-polar, to ensure isolation between them.Figure 19 shows the scatter parameters measured in the anechoic chamber.

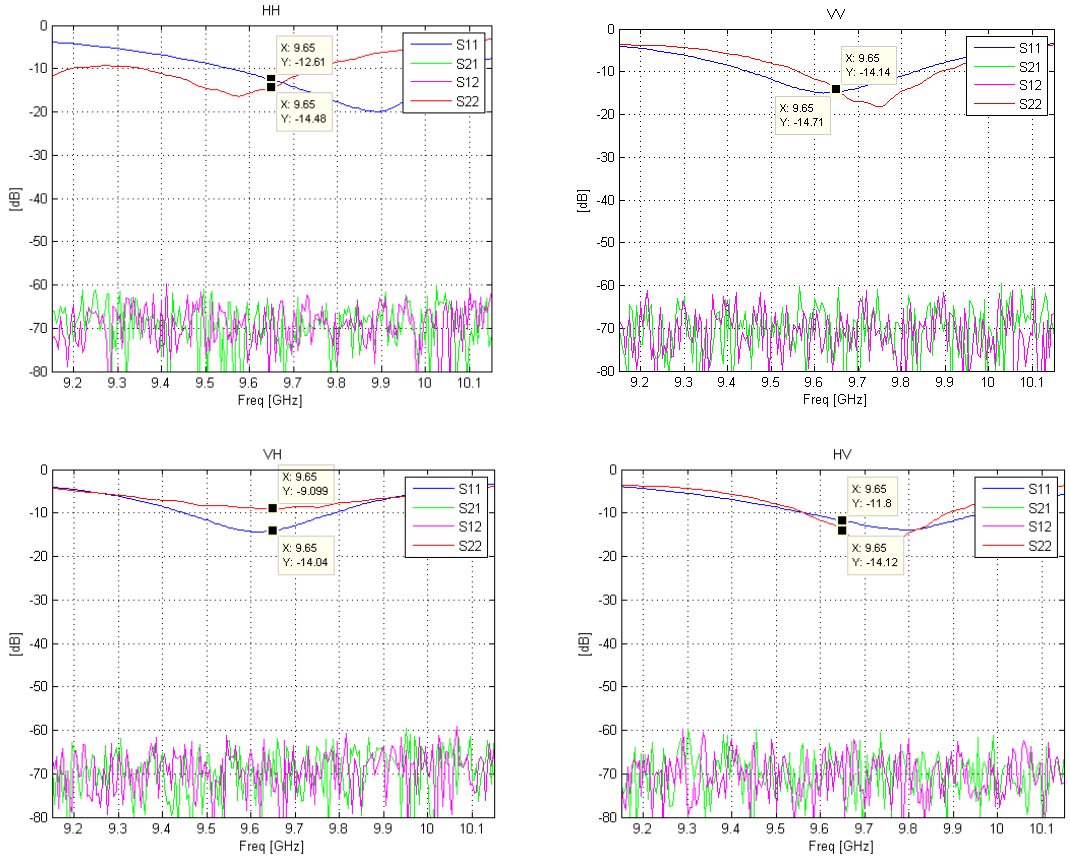

Figure 19. Antenna coefficients with its polarizations

In Figure 19 can be seen that the antennas have an acceptable return loss, under -14dB, and the isolation is around -70dB.

The transmission of the Tx antennas it's managed by a solid state switch (model MASW-008322 [9]). This switch goes placed between the two transmitter antennas (Figure 20). The active polarization depends of the signals V1 and V2 received from the CTRL_Pol board

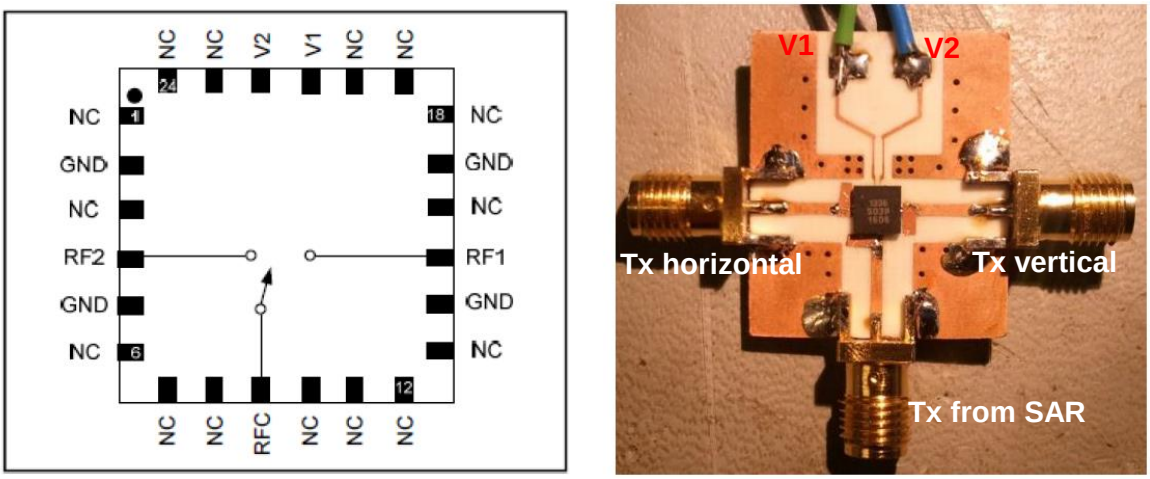

Figure 20. MASW-00382 switch and its mount on a PCB plate

The CTRL_POL board has two main inputs. One it's coming from the Arduino trigger system, which activates the polarization system once it's enabled, and the SAR control

inputs which are the PRF (Pulse Repetition Frequency) signal, a positive voltage signal (14'8V), a negative voltage signal (-13'3V) and ground (GND) reference.

The PRF signal is inverted with a 74F04 inverter for timing, in order to be able to switch the polarization by taking a falling flank in the PRF, and it's divided in half with a 74F74 device. The PRF signal divided by 2 (POL in Figure 21) it's used as a control signal for generate V1 and V2 signals that will activate vertical and horizontal polarization. The truth table of the board can be seen in Table 7. The acquisition of data is made when an ascending flank is detected. In that way it's avoided to take the signal in a transitional stage (as it can be seen in Figure 21). The polarization signals +5V and -5V for polarization of the P-transistors (model BSS85) are generated by voltage regulators.

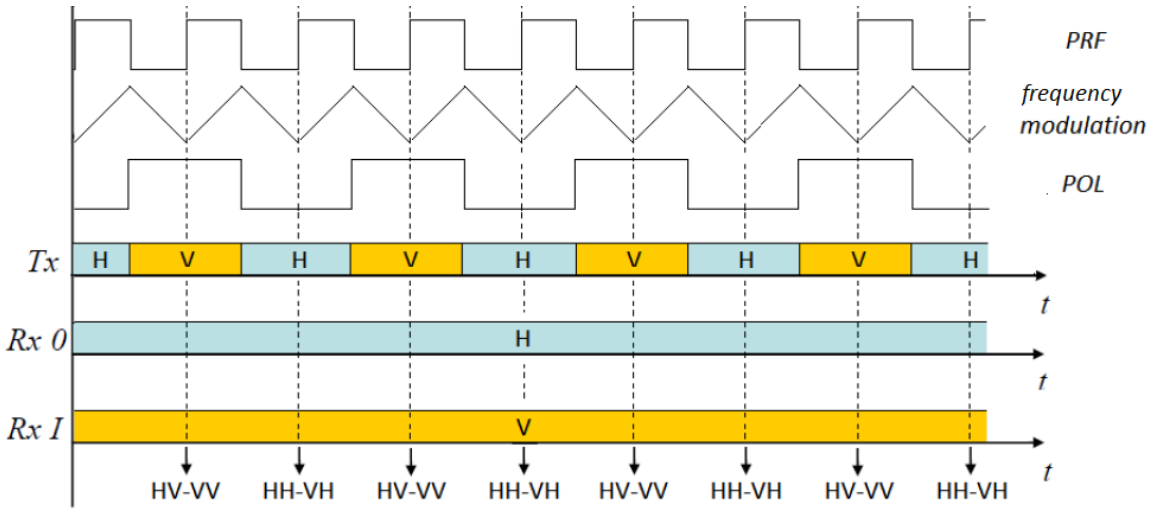

Figure 21. Representation of ARBRES-X timing diagram during measurements

By acquiring data from channel 0 and 1 at the same time, as it can be seen in Figure 21, in two PRF periods, it can be acquired data from all polarizations (HV, VV, HH, and VH)

IN	V1	V2
0	0	-5
5	-5	0

Table 7. Switch's table of truth

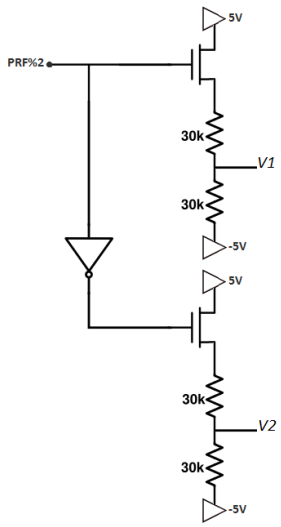

Figure 22. Switch signal generator schematic

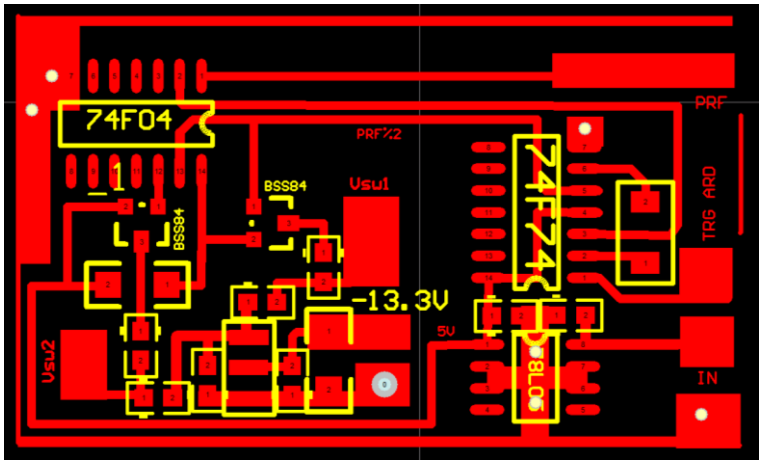

Figure 23. CTRL POL PCB board

In Figure 23 can be seen the schematic of the PCB board where the circuit is installed. It has a dimensions of 4 x 2'5 centimetres.

3.2.2. **Reduction of noise and spurious in the Rx chain**

Measuring the reception chain in the ARBRES-X SAR system a high background noise and high spurious that affected our received signal was found (Figure 26). After inspecting the complete reception chain was discovered that the background noise was caused by a bad isolation of voltage supply lines. After replacing these lines by shielded cables this noise was reduced (Figure 27). In the case of the spurious it was studied that may be caused due to the coupling of the switching regulators. The power amplifier in the DDS it's powered by a PTN78000 switching regulator by texas instruments. By looking at their datasheet [10] it was found that it was recommended to install pi filters at the input and output of the regulators as shown in Figure 24. These filters were installed directly on the switching regulator, as shown in Figure 25.

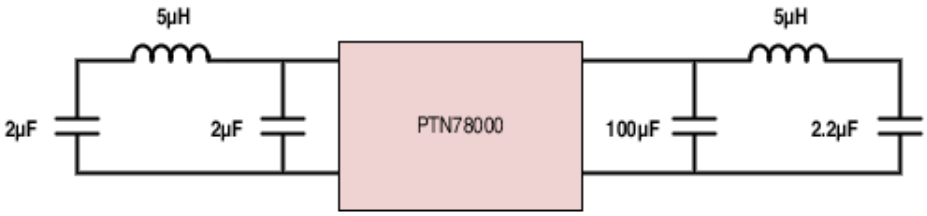

Figure 24. Design of the filters assembled for the switching regulator

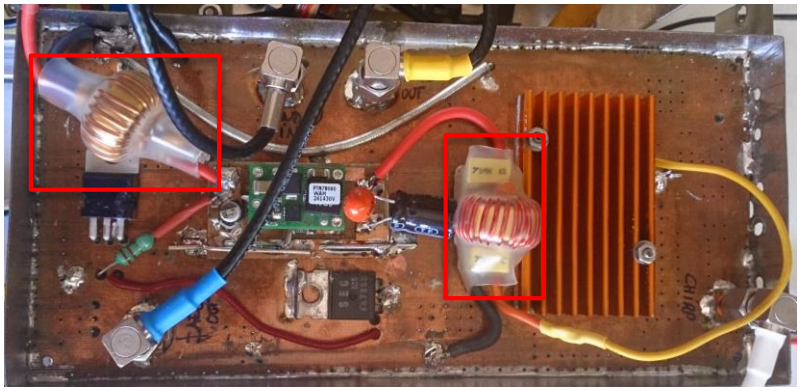

Figure 25. Pi filters installed in the switching regulators, covered by heat shrink sleeve

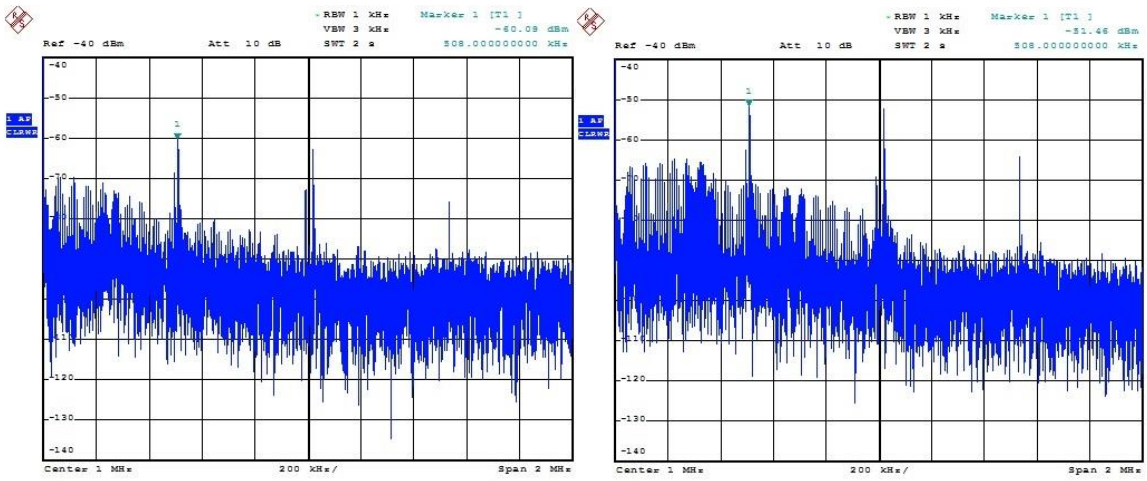

Figure 26. Measurement with the spectrum analyzer of channel 0 (left) and channel 1 (right) before the improvements

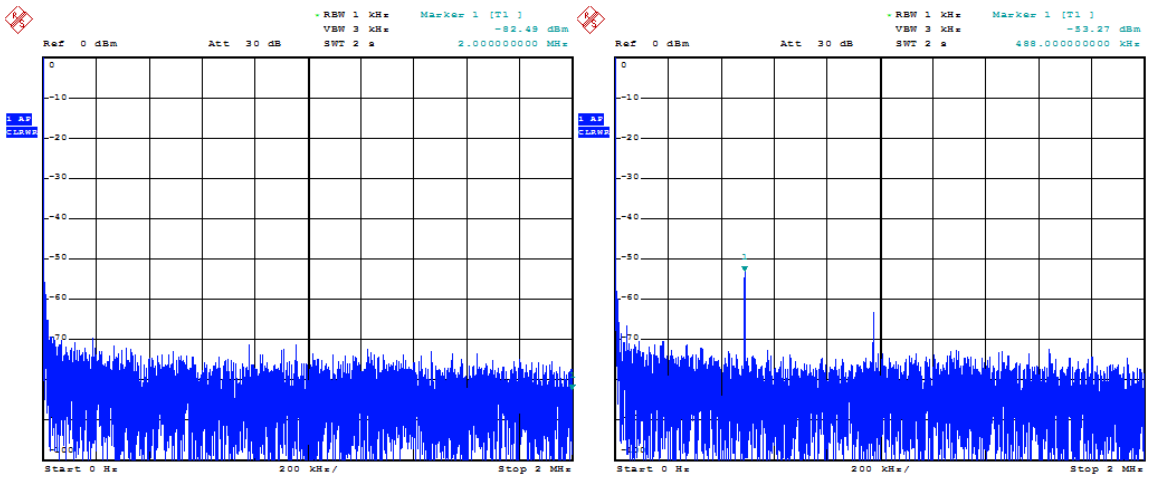

Figure 27. Measurement with the spectrum analyzer of channel 0 (left) and channel 1 (right) after the improvements

By comparing Figure 26 and Figure 27 it can be seen that the noise figure was reduced in both channels. The spurious in channel 0 disappeared. In channel 1 a spurious at 490 KHz it's still appreciable with a power of -53dBm. This spurious should have an impact on the image at a distance of 70 meters, but since it has such a low level of power, this effect may be despicable.

After all the improvements, it was measured that the reception chain has a total gain of 70dB. The LNA stage has a gain of 20 dB for each channel, but their coaxial cables, because of their flexible construction for support movements, they have 2dB loss. The reception box inside the SAR system has a gain of 52dB.

3.3. Complementary hardware development

To complete the system, some devices were needed to be developed in order to work as a bridge between the SAR system and the octocopter (Arduino trigger system in 3.3.1), to improve the pointing and stability of the antennas (gimbal stabilizer in 3.3.2) and the processing of the image by motion compensation (XSens system in 3.3.3).

3.3.1. **Arduino trigger system**

An input signal is needed in order to activate a logic door for shooting the SAR system. In this case a 5V output signal with a duration of 12 seconds is used. For making that signal, an Arduino mini controller is used.

Three different ways to initiate an acquisition have been designed. The first one is by assigning a channel in the RC controller and connecting a servo cable from the RC receiver to the Arduino platform. This is used for making apertures that were not previously programmed. Other way for triggering the system is using the F2 channel coming from the A2 controller, using the servo action (as was explained in section 3.1.3). This is also used for powering the Arduino controller without the usage of an external battery. The other way it's by pressing a button installed in the same board of the Arduino. This is useful for making tests without having to connect the RC receiver or the A2 controller, rather than making apertures. Figure 28 shows the wiring diagram in this system.

Once the Arduino receives the order, four outputs signals are generated. The main one is used for the SAR triggering. Another one it's for turning on a led for having a visual confirmation that the trigger is working. Other signal is sent to the antenna bar to activate the switch (as was explained in section 3.2.1). The last signal is sent to the XSENS sensor, to acquire inertial data during the measurement, as it will be explained in detail in section 3.3.3.

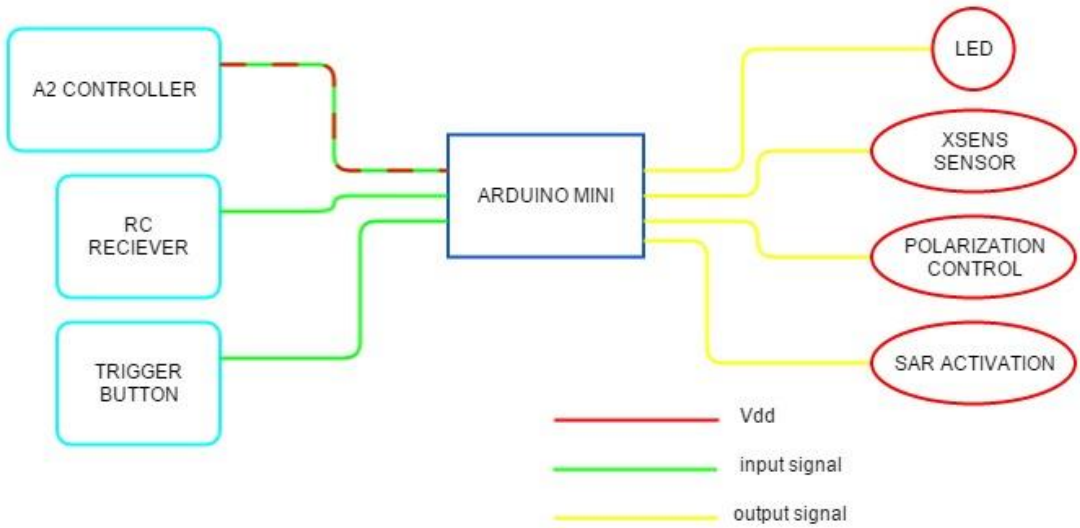

Figure 28. Arduino trigger diagram

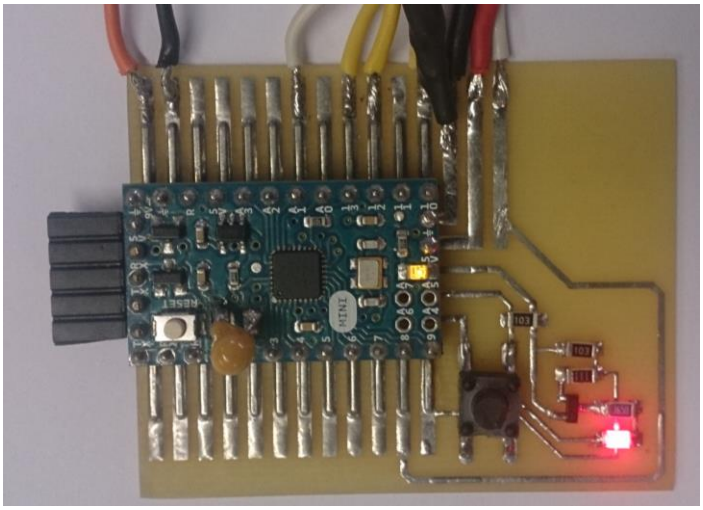

Figure 29. Arduino trigger mounted on a PCB

In Figure 29 the system can be seen with all wires attached. The PCB plate goes placed directly on the top of the octacopter by using double-sided tape. An Arduino mini controller was chosen for this function, due to its small dimensions and its low power consumption.

3.3.2. **Gimbal stabilizer**

Unlike a plane, a multicopter platform has to play with its pitch angle in order to flight horizontally. The more pronounced is the angle, the higher speed it reaches. To keep in horizontal position the lightweight bar with the transmitting and receiving antennas, a gimbal stabilizer has been developed.

Due to the weight and inertia of the bar where the antennas are mounted, a powerful servo was necessary for that task. The servo used was an RCtecnic S0150 with a voltage regulator LM7805 (5V). An Arduino nano microcontroller was chosen to control the servo due to its compact size and its compatibility for communicating via I2C (Inner Integrated Circuit), necessary for the usage of an imu sensor. The inertial sensor chosen after a few tests was the Pololu AltIMU-10. This model of servo can be wired directly to the battery but, after seeing that the bar suffered very strong oscillations, it was needed to place a regulator between the battery and the servo, in order to power it with a stable voltage tension.

The Arduino board has a 9V terminal that it's used to attach the 7,4V battery. For wiring the imu sensor, the SCL (Serial Clock Line) port needs to be attached to the A5 terminal in the Arduino and the SDA (Serial DAta line) port, to the A4. It's fed by using the 3,3V port in the Arduino board. For connecting the servo to the Arduino the terminal 8 it's used. It's important to connect the ground node of the servo directly to the ground node in the regulator, because the ground line in the Arduino presents a resistance that slows down the servo movement. The wiring schematic can be seen in Figure 30. The servo was attached to the SAR box by cutting a metal plate and fixing it with screws. The Arduino board and the imu were fixed by using double sided tape. For the imu, neoprene cuts were also used in order to absorb small oscillations that are produced by the platform, as it's shown in Figure 30.

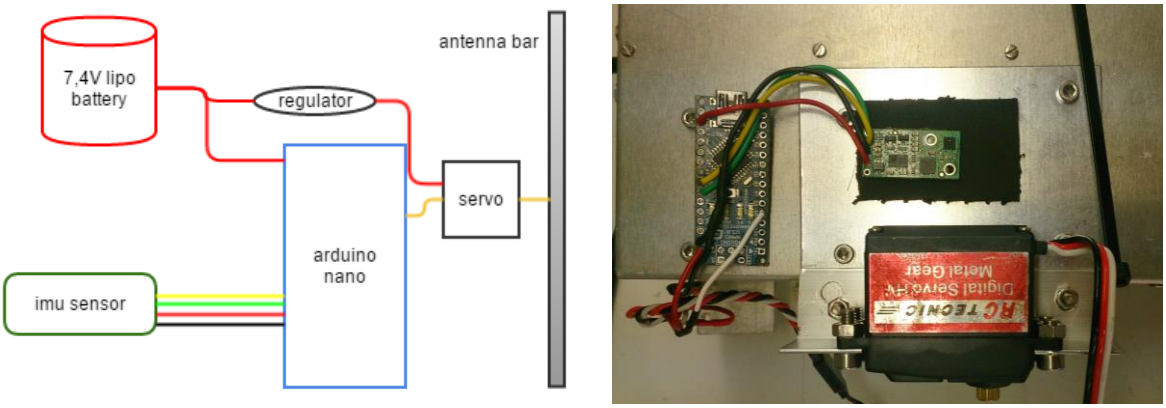

Figure 30. Gimbal diagram (left) and its build below the SAR box (right)

3.3.3. **XSens System**

During the acquisition time, the UAV multicopter platform, should follow a perfect straight trajectory with a uniform speed. In practice, however, there are variations than must be taken into account such as speed, altitude, pitch, roll and yaw. The impact of this variations is bigger in multicopter UAVs than in planes, which have a bigger stability on air because of its longer fuselage and its higher speeds. X-Band (9,65GHz) has a wavelength of 3'11cm, so any small variation in the position leads to a big change in the phase of the signal. One of the studied ways for applying motion compensation it's by acquiring inertial data during flight and then, in the focusing algorithm, applying this data at the phase of the signal.

A first prototype for acquiring inertial information was by adding an Arduino mega controller with a Razor IMU and a small GPS sensor. All this data was being constantly acquired and was delimited with the beginning and the end of an aperture. All the data was stored in a microSD card connected to the Arduino. This method was discarded because the acquired data was irregular during time and the start and finish flags weren't clear, and didn't have a watch reference.

Finally it was decided to mount an XSens sensor, composed by an IMU sensor and a GPS. It also has a barometer integrated. This is a high end sensor and it's capable to acquire telemetry data directly to the ARBRES-X SAR System via USB. It provides its own software for configuration. It also goes connected to the Arduino trigger system in order to delimit the aperture time. The system mounted in the UAV multicopter platform can be seen in Figure 31. A small sponge is placed on a side of the XSens sensor in order to prevent interferences caused by the wind on the barometer

The XSens bring us data about altitude, latitude, longitude, pitch, roll and yaw. All this data can be read easily by using Matlab. It also provides a plugin in order to see the flight trajectory in google maps as can be seen in Figure 32.

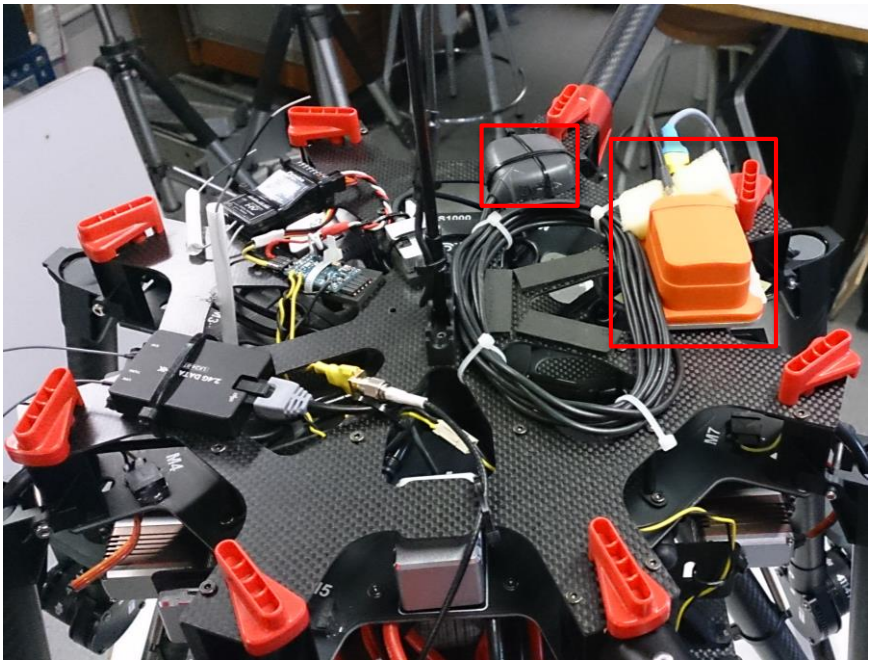

Figure 31. XSens sensor (orange) with gps (black) mounted

Figure 32. Example of the trajectory of the UAV multicopter platform provided by the XSens by using Google Earth

4. Results

Some measurements were made with the system, using singlepol and fulpol capabilities. Also, some motion compensation algorithms were applied in order to improve the images obtained. The whole hardware system mounted can be seen in Figure 33.

Figure 33. SAR System completely mounted at Ripollet test site.

4.1. Single pol results

For single pol images, only one antenna in transmission and reception is used. In this case, due that it has a better quality, channel 0 was used.

Figure 35. Ripollet test site

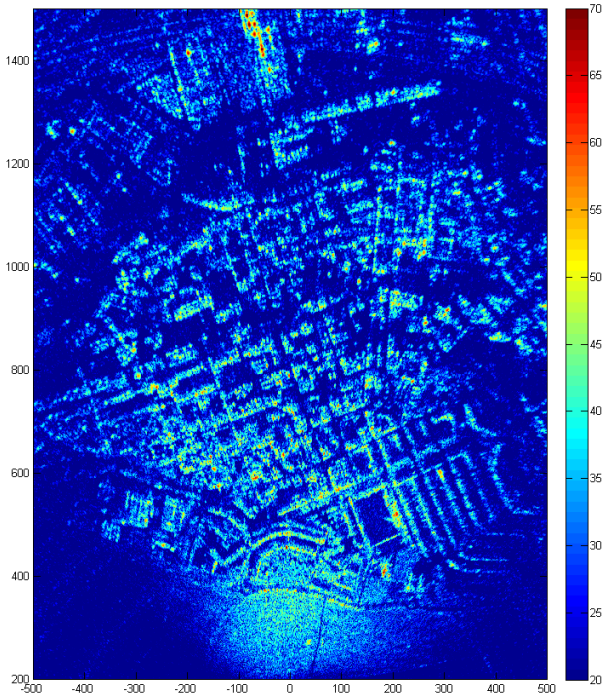

Figure 34. Single pol image obtained of the Ripollet test site

In Figure 34 can be seen that the Single Look Complex (SLC) image obtained has a good resolution without applying any kind of motion compensation. Comparing the measurement of Figure 34 with the aerial view of the Ripollet test site shown in Figure 35, buildings, roads, roundabouts and fields are easily recognizable. As we move away we can see how the resolution is decreasing. The image has a lower level of power on the upper side of the image. This is because the image was taken flying at 200 meters of altitude and the platform didn't have a visual angle of the complete test site. This creates more blind spots of the image. The darker spots on the lower corners are due to the radiation patern of the antennas used. There's no effect from spurious at the image.

4.2. Full polarimetric results

In order to evaluate the full polarimetric capabilities of the ARBRES-X SAR System, some measurements have been performed. Figure 36 and Figure 37 show an example of full polarimetric measurement measured in the Ripollet test site.

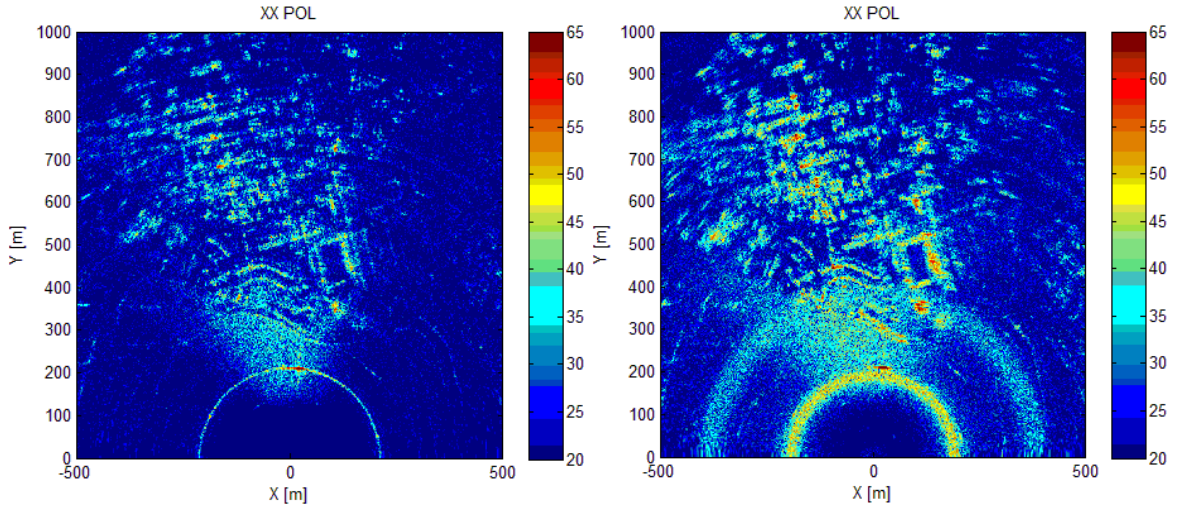

Figure 36. Ch0 and Ch1 copolar images

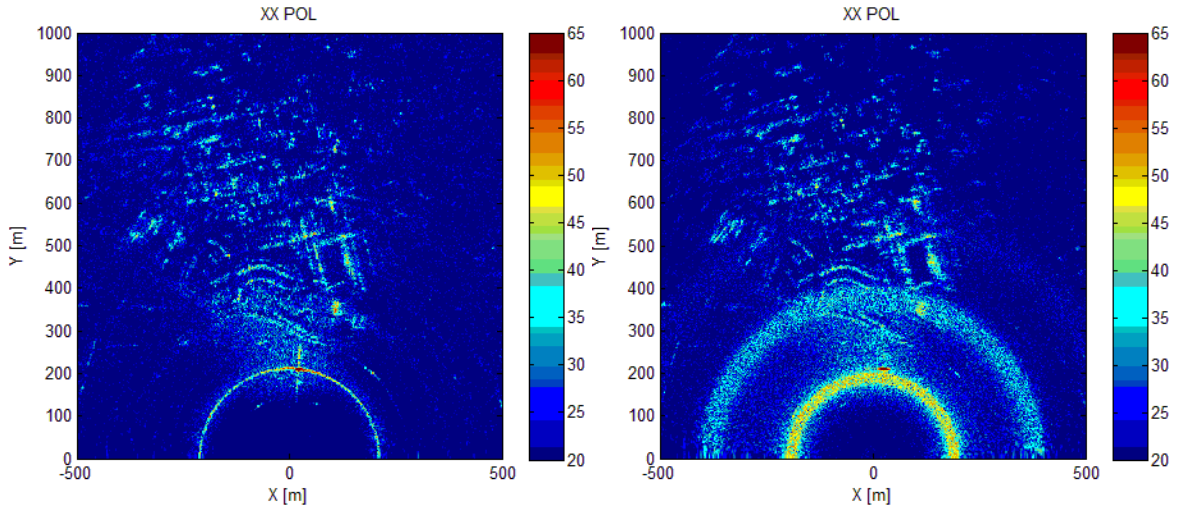

Figure 37. Ch0 and Ch1 crosspolar images

By the SLC images shown in Figure 36 and Figure 37 can be seen that the fulpol images obtained have much less power than in the case of singlepol (Figure 34). This is due that by making more images during the same aperture time, less signal it's used for each one, which leads to have less energy. They also have a much lower resolution. It can be seen that in channel 1 are interferences at approximately 100 meters. As expected, there are no interferences at 70 meters caused by the spurious detected in Figure 27. After inspecting the whole reception chain it was found that the problem it's produced inside the acquisition card and, by the moment, can't be solved.

4.3. Motion Compensation techniques

For improving the quality of the images obtained a few methods were tested.

It was scheduled to use the data acquired by the XSens sensor in order to modify the phase to improve the focalization, but the data acquired was completely useless, despite of having recalibrated the sensor and tried different configurations provided.

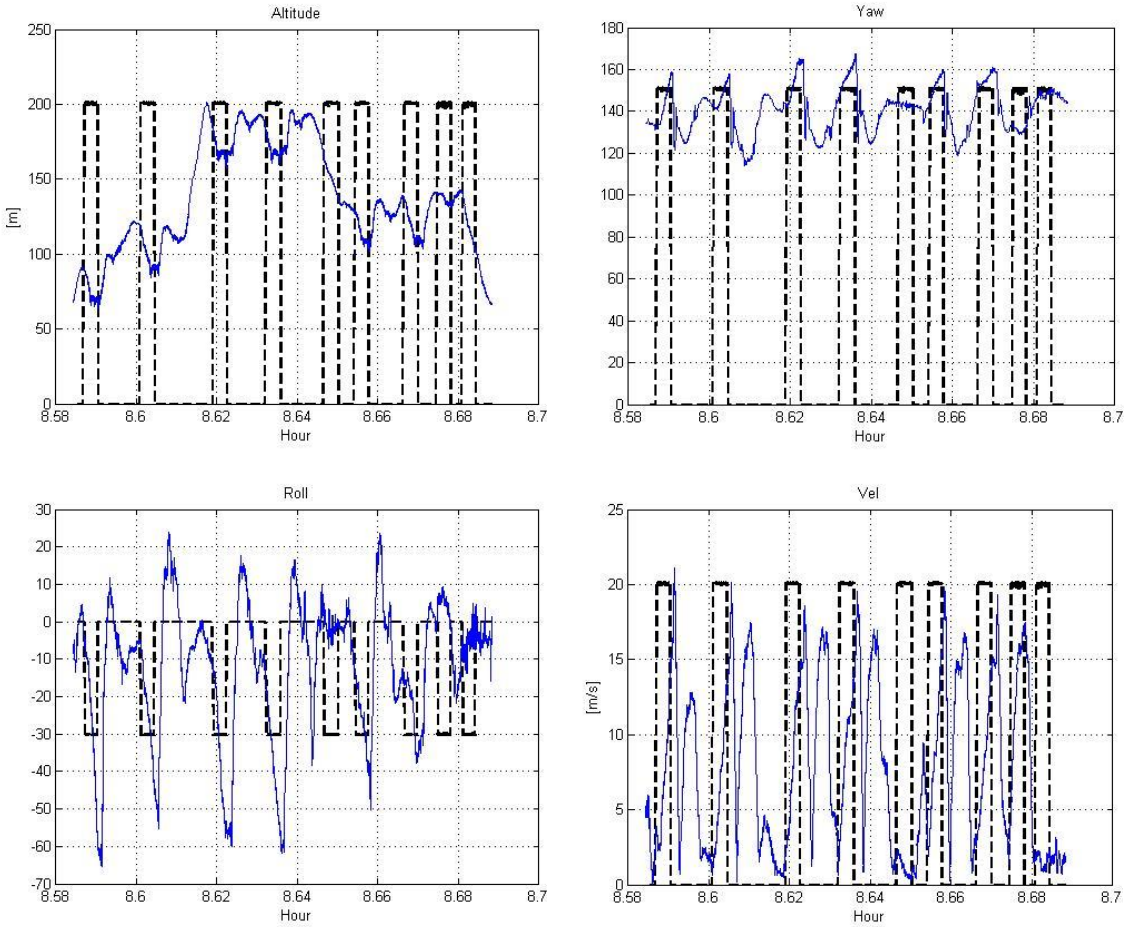

Figure 38. Telemetry data acquired from XSens

It can seen that the variations displayed at the images in Figure 38 don't correspond to real data from the flight. As an example, the alttitude variations obtained during the apertures, which are marked with black pulses at the images (obtained by the signal generated by the Arduino trigger system as was explained in section 3.3.1) it's supposed to be stable, but variations of over 40 meters can be seen.. The yaw angle variations should be very small, because the apertures are straight lines, and in flight there aren't made any turns, but we see changes like the platform was spining in that period.

Figure 39. Flight trajectory displayed with Google Earth

In Figure 39 can be seen that gps coordinates are not good. The coordinates describe impossible flights.

Since the data obtained by the XSens system is not usable, an autofocus method was applied in order to improve the quality of the images. By watching the phase story from a certain point of the image and comparing it to the ideal phase story, a correction of the phase can be applied.

A device with a high reflectivity (PARC) was placed in the Ripollet test site in order to evaluate its phase story.

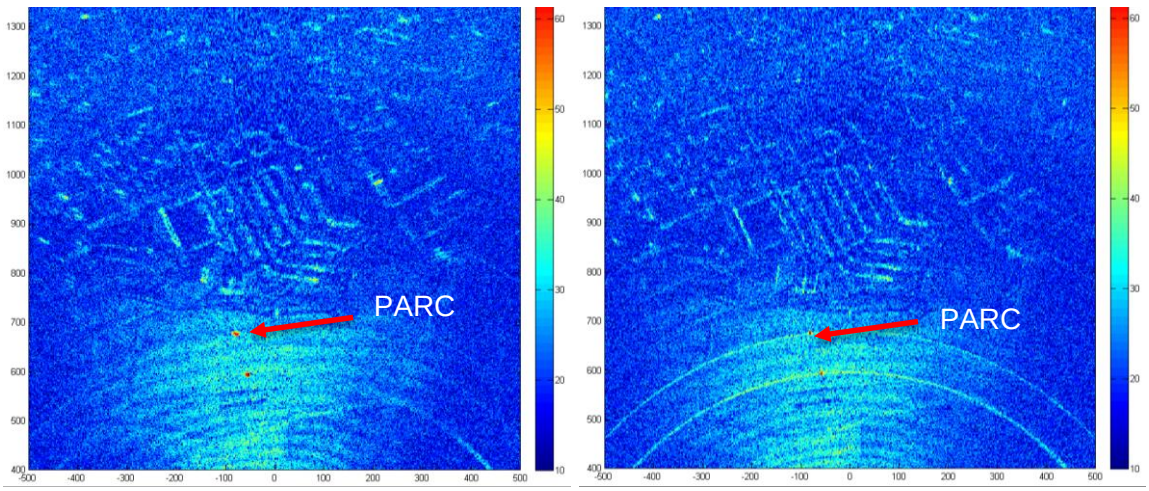

Figure 40. Image before and after applying autofocus method

We can see at the image improved its overall resolution, especially around the PARC reflective point. Even though the farther points of the image have reduced its quality. This is because they may have a different error phase than the one applied.

In Figure 41 this blur effect in distant points it's more evident. The PARC device it's barely apreciable, and the right part of the image improved its quality also, but at the left part, the buildings are more blurred. This is because that it cannot be applied the same

compensation phase to all point of the image because each one may have a different phase story during the aperture.

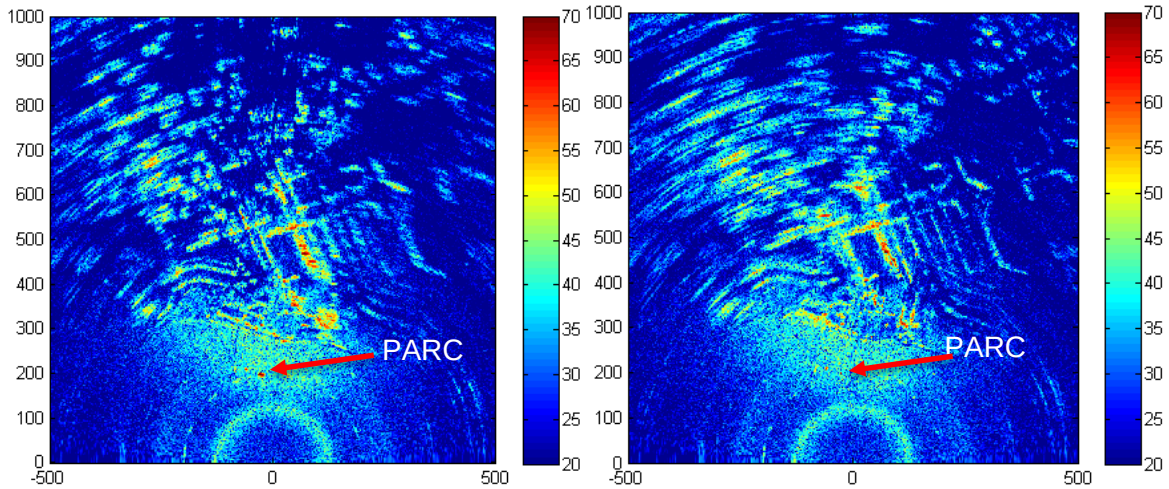

Figure 41. Another example before and after applying autofocus method

After analysing the behaviour of the UAV multicopter platform, it has been found that the speed variations of the platform have a bigger impact on the images than expected. By having into account a small variation of the speed, as can be seen in Figure 42, the quality of the image was improved, as it can be seen in Figure 44.

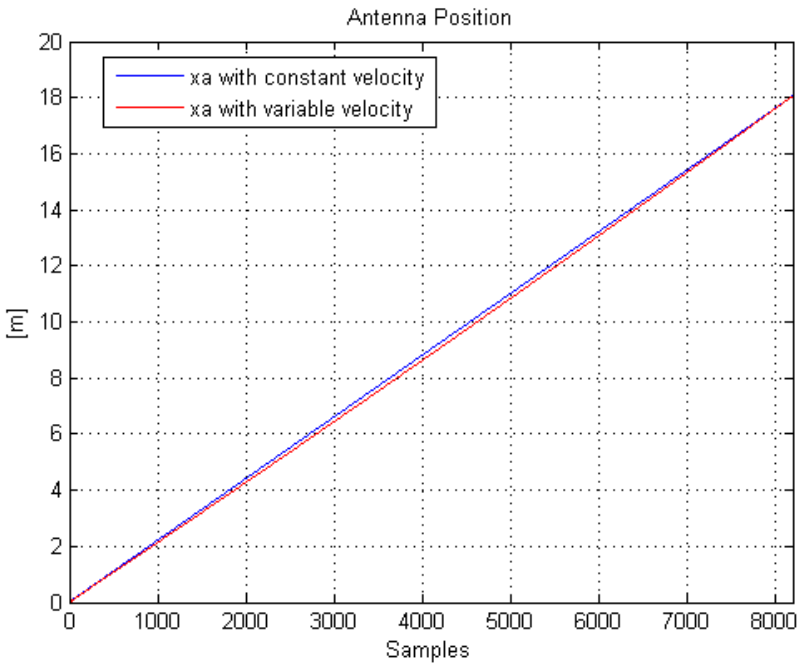

Figure 42. Comparison between having a constant velocity (blue) and a variable velocity (red)

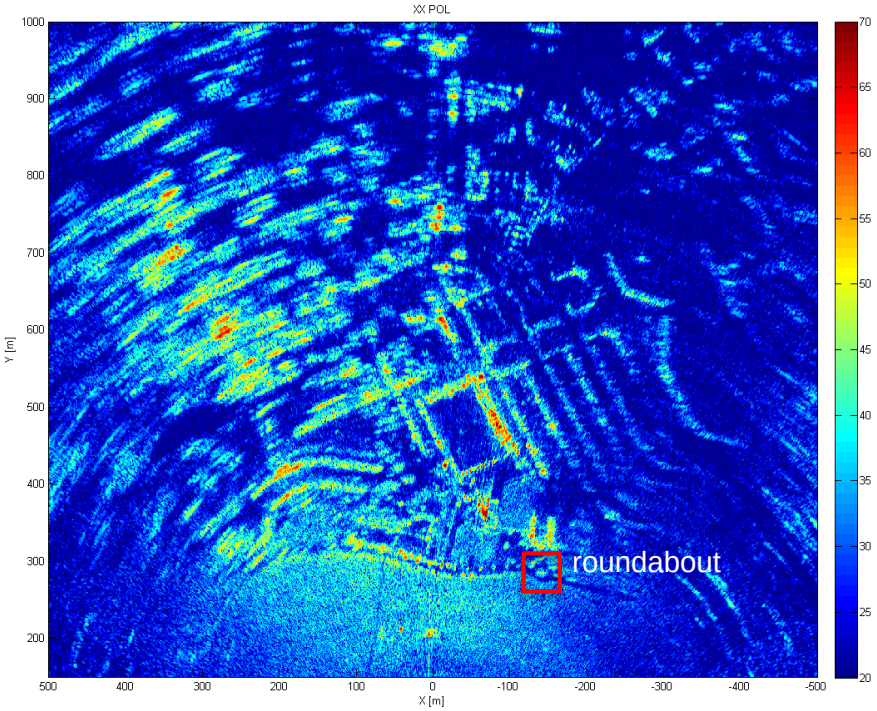

Figure 43. Image obtained with constant velocity

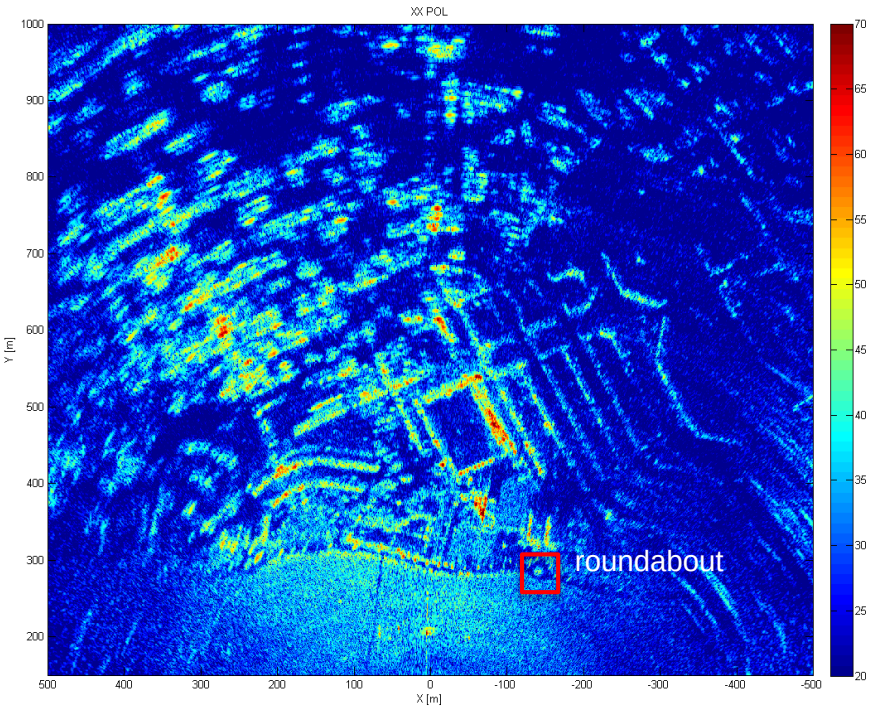

Figure 44. SLC Image obtained with variable velocity

By comparing Figure 43 and Figure 44 the improvement of the image it's noticeable. The roads and the streetlights gained a lot of definition, especially on the lower part of the image. As an example, the roundabout marked in red recovered its round shape. The buildings, especially on the left side of the image, can be better distinguished from each other.

5. Budget

For making this budget, it has been taken in account the price of the hardware components and the hours invested as a junior engineer:

Equipment	Cost
Dji S1000 octocopter	3,390€
A2 controller kit	1,099€
Dji Ground Station kit	449€
Futaba T10J RC controller	304€
Multicopter batteries	6 x 115€
ARBRES-X main components	2725€
ARBRES-X batteries	150€
Arduino controllers	50€
Servo S0150	20€
XSens sensor kit	7,000€
TOTAL	**15,877€**

To calculate the cost of the ARBRES-X system, it was taken in account the price of the main components (circuit board, processor, ram unit, and the acquisition card), but it must be taken in account that the system it's a singular product, so it's real price can't be calculated.

The hours invested on this project are approximately 400 hours, and by perceiving 8€/hour this cost raises to 3200€.

The final total cost of this project makes a total of **19077€.**

6. Conclusions and future development:

6.1. Summary

With this thesis it's proven that, despite of its limitations, an UAV multicopter platform it's capable to carry efficiently a SAR system.

Thanks to the capability of the UAV multicopter platform to perform preprogramed routes combined with the automatic trigger of the SAR system developed during the present degree thesis, autonomous measurements with the ARBRES-X SAR system can be performed. Besides, the versatility of the UAV multicopter platform makes the system capable to take off and land in almost any place, without the dependence of a runway needed by other UAV platforms such as an RC airplane.

The design of the lightweight aluminium bar, comprising the four patch antennas, the solid state switch, the CTRL POL board and the LNAs has been successfully developed without compromising the stability of the platform. Also, the gimbal system implemented was able to keep the antenna array in horizontal position, maintaining the correct polarization of the antennas during the entire aperture.

After some hardware improvements in the ARBRES-X SAR System, especially in the receiver chain, the quality of the acquired data has been upgraded. A high noise level was found in the receiver chain that was caused by a bad isolation of power lines and the coupling of switching sources. After isolating the power lines and filtering the switching sources, a reduction of the noise level and spurious was achieved.

Despite of not being able to use the acquired inertial data from the XSens system (due to factors beyond our control), some autofocus methods were applied in order to improve the quality of the processed images. Concretely, the effect of having variations on the velocity of the platform, which must be taken into account, has been studied. The results are optimistic and leads the project to point towards new applications, such as applying multipass interferometry.

As the work was developed on an investigation project, following a time plan was difficult because a lot of objectives were defined on the go. Also, by working mainly with hardware, suffering incidences it's more common than with software, leading to produce bottlenecks to the entire project.

On my personal experience, getting into a work environment in the university outside the classroom taught me a lot about how projects are handled. Working on a laboratory in order to advance in a bigger project I found it more motivating than just following a mark for passing an exam. Also this work helped me to develop my skills in other fields, such as Arduino programming, and managing hardware inside a laboratory.

6.2. Future Development

The product of this thesis can be expanded in the following ways:

1. Reduce the interferences effect in channel 1 in order to acquire properly with this channel
2. Reduce the amount of batteries used in order to reduce weight and gain autonomy.

3. Reduce inertia of the bar by reducing weight and longitude on it as possible.
4. Fix the XSens system to be able to apply motion compensation algorithms with the data retrieved.
5. Achieve stable velocities in the UAV platform during apertures in order to reduce the effect of speed variations in the processed images.
6. Be able to control automatically the polarizations used by the platform.

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Appendices:

The Arduino codes developed during this work and the two can be found in the attached file “Annex.zip”.

Glossary

SAR: Synthetic Aperture Radar

UAV: Unmanned Air Vehicle

RADAR: RAdio Detection And Ranging

ARBRES: Air Based REmote Sensing

UPC: Universitat Politècnica de Catalunya

RC: Radio Controlled

SLFM-CW: Stepped Linear Frequency Modulated Continuous Wave

DDS: Direct Digital Synthesizer

PRF: pulse Repetition Frequency

BPA: Back-Projection Algorithm

FFT: Fast Fourier Transform

MoCo: Motion Compensation

LNA: Low Noise Amplifier

IMU: Inertial Measurement Unit

GPS: Global Positioning System

V: Volt

I2C: Inner Integrated Circuit

SDA: Serial DAta Line

SCL: Serial Clock Line

GND: GrouND

Fulpol: Full Polarimetric