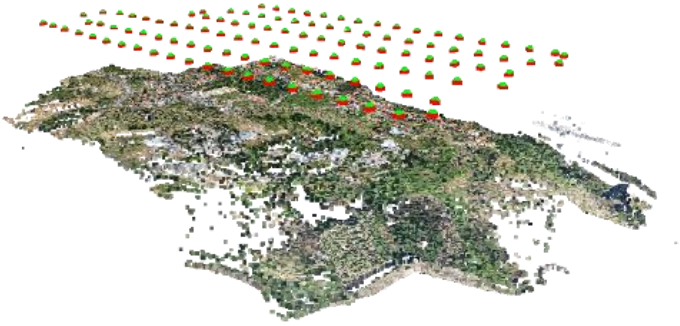

Evaluation of Photogrammetric Solutions for RPAS: Commercial vs Open Source

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Summary

The means to achieve aerial photography changed with the emergence of a new revolutionary type of vehicle: Remotely Piloted Aerial Systems. The developments of those vehicles in the past few years, brought a large number of companies offering services related to aerial imagery, from surveys, media, precision agriculture, among others. Even in the scientific community, this new technology opened up new ways and processes to investigate in a huge range of different fields.

Several studies already testified the usefulness, advantages and precisions achieved using those vehicles, against traditional methods. The low operational cost and versatility were important conditions that pushed these vehicles forward in businesses and Universities all over the world. Nowadays digital photogrammetry thrives with the recent years development of software, accessible to broader public, even to non-experts in that scientific field. New software were built with the latest evolution of computer vision algorithms, bringing photogrammetric solutions in conjunction with Unmanned Aerial Vehicles, available to more and more people, from hobby to professional purposes.

For this study is intended to analyze several regions of interest, processing with 3 chosen photogrammetric software: PhotoScan, Pix4Dmapper and MicMac. Two of them represent the 2 best seller commercial solutions, along with an open source version, in order to compare several features between them, to evaluate their performance in distinct scenery.

Errors in geolocation are examined, confirming other recent scientific studies that MicMac is able to achieve the best results in photogrammetric reconstruction. Other more subjective features, such as radiometric equalization and building edges, are not always explored in studies, but are also key aspects to analyze. Even more when the final objective is to use this data in business environment, and normally those features varies between each software. In fact, the open source solution has the worst results in radiometric equalization and mosaicking, already with solutions being developed by the software team, but on the other hand presents some of the best results with sharp build edges, something that Pix4Dmapper fails most of the times. PhotoScan reveals to be the most consistent in the overall performance in georeference, reconstruction and visual portrayal.

Key Words: RPAS, PhotoScan, Pix4Dmapper, MicMac, Photogrammetry, Open Source, commercial, Orthomosaic, DEM, precision, performance, comparison, RGB, NIR

Resumo

Os meios para obter fotografia aérea mudaram com um novo tipo revolucionário de veículo: Veículos Aéreos Não Tripulados. A evolução desses veículos nos últimos anos trouxe um grande número de empresas que oferecem serviços relacionados a imagens aéreas, desde levantamentos aéreos, comunicação social, agricultura de precisão, entre outros. Mesmo na comunidade científica essa tecnologia abriu novos caminhos e processos para investigar numa enorme variedade de campos.

Vários estudos já comprovaram a utilidade, vantagens e precisões usando esses veículos contra os métodos tradicionais. O baixo custo operacional e versatilidade foram condições importantes que impulsionaram esses equipamentos a serem usados em empresas e universidades em todo o mundo. Atualmente a fotogrametria digital prospera com o desenvolvimento de software acessível ao público em geral, mesmo para quem não é especialista nesse campo científico. Novos software foram construídos com a mais recente evolução de algoritmos de visão computacional, trazendo soluções fotogramétricas, em conjunto com veículos aéreos não tripulados, disponíveis para mais pessoas, desde o hobby até aos fins profissionais.

Para este estudo pretendem-se analisar diversas regiões de interesse, processando com 3 software: PhotoScan, Pix4Dmapper e MicMac. São 2 dos mais vendidos em termos comerciais e um de código aberto para comparar recursos entre eles, a fim de avaliar o seu desempenho em cenários distintos.

Erros em geolocalização são examinados, confirmando estudos científicos recentes, que o MicMac é capaz de alcançar os melhores resultados na reconstrução fotogramétrica. Outras características mais subjetivas, como equalização radiométrica e limites de edifícios, nem sempre são exploradas, mas também são aspetos fundamentais para analisar, ainda mais quando o objetivo final é usar esses dados em ambiente empresarial, e normalmente esses resultados variam entre cada software. Na verdade, a solução de código aberto tem os piores resultados na equalização radiométrica e construção de mosaico. No entanto está a ser desenvolvida solução pela equipa do software, mas por outro lado apresenta alguns dos melhores resultados com limites de edifícios, algo que Pix4Dmapper falha na maioria das vezes. PhotoScan revela ser o mais consistente no desempenho global em georreferenciação, reconstrução e representação visual.

Palavras-chave: RPAS, PhotoScan, Pix4Dmapper, MicMac, Fotogrametria, Open Source, comercial, Orthomosaic, DEM, precisão, desempenho, comparação, RGB, NIR

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Acronyms List

UAV – Unmanned Aerial Vehicle

RPAS – Remotely Piloted Aerial System

GNSS – Global Navigation Satellite System

DEM – Digital Elevation Model

FCUP – Faculdade de Ciências da Universidade do Porto

UPTEC – Parque de Ciência e Tecnologia da Universidade do Porto

RTK – Real Time Kinematics

RGB – Red, Green and Blue

NGB – Near InfraRed, Green and Blue

IMU – Inertial Measurement Unit

SIFT – Scale Invariant Feature Transform

RANSAC – Random Sample Consensus

GCP – Ground Control Points

NIR – Near InfraRed

3D – Three Dimensions

APM – ArduPilot Mega

DSLR – Digital Single-Lens Reflex

SAR – Synthetic Aperture Radar

LIDAR – Light Detection and Ranging

DTM – Digital Terrain Model

IGN – Institut National de L'Information Géographique et Forestière

GUI – Graphical User Interface

CNES – Centre National d'Études Spatiales

ETRS89 – European Terrestrial Reference System 1989

PTTM06 – Portugal Transverse Mercator 2006

EPSG – European Petroleum Survey Group

QGIS – Quantum GIS

GDAL – Geospatial Data Abstraction Library

UTAD – Universidade de Trás-os-Montes e Alto Douro

WGS84 – Word Geodetic System 1984

FTP – File Transfer Protocol

LNEC – Laboratório Nacional de Engenharia Civil

XML – Extensible Markup Language

DSM – Digital Surface Model

RMS – Root Mean Square

GSD – Ground Sampling Distance

1. Introduction

1.1. Current Technology Setting

Nowadays is obvious an exponential growth in this new kind of airborne vehicles into the most diverse applications imaginable. Several names have been suggested to describe those vehicles, from Unmanned Aerial Vehicle (UAV), one of the most known forms, to Drones, which have been known to the public for several years now, due to the military applications.

The evolution of civil Remotely Piloted Aerial Systems (RPAS) [1] was also powered by the hobby activity of aero modeling. For years, people associated with this hobby, built miniaturized plane models and helicopters with little electronic components, being the most import the radio transmitter and receiver for controlling the aircraft. With the popularization of Global Navigation Satellite Systems (GNSS) receivers and development of low cost and even Open Source automatic piloting electronic boards, the small sized RPAS thrived and rapidly entered our lives.

The affordable components of the RPAS contributed to the rising of several businesses in various fields of action that saw an opportunity to innovate, be cheaper than the usual solution and be ahead of the others.

In Surveying Engineering, the most sought out purpose for the RPAS is aerial photography in order to produce orthomosaics and Digital Elevation Models (DEM). Through the process of photogrammetry is possible to get accurate measurements and 3D modeling of the relief and buildings, by calibrating and stitching aerial imagery with a certain overlap between them [2].

To the media it is a powerful tool of work, giving access to new angles of filming and a new perspective over locations for news reports with a much lower cost than traditional helicopters and filming cranes. The same can be applied to the authorities' forces such as police, Special Forces and army. These vehicles give them the possibility to monitor for example coastal areas for traffic and drug smuggling, counting the number of people in public events like football games, concerts, or even in more extreme cases such as riots [3].

Another field of application is the agriculture and forests. As RPAS can be equipped with a huge variety of sensors, from near infrared to calculate vegetation

indices, to thermal cameras to pinpoint the location of hot spots in forest, allowing a faster response from the governmental forces to prevent forest fires [4] [5].

Whilst there are a vast number of business dedicated exclusively to RPAS, countries like Portugal still lack legislation to accommodate such technology in the skies in conjunction with civil aviation. Reports about incidents involving those vehicles with people and even manned aircrafts are getting more and more visibility to the public opinion. Currently the European Commission is preparing some form of rules to be applied throughout the European Community, including Portugal [6]. Although several countries already adopted some kind of legislation, Portugal still maintains a void in this matter, allowing drones to fly unsupervised and without certification. The best hope for some kind of ruling is in 2016 when the European Commission releases the first laws.

1.2. Objectives

With this study it is intended to better understand and evaluate the performance between photogrammetric solutions, commercial and open source, in order to use them in professional applications in a small project born from Faculty of Sciences in University of Porto (FCUP) students, including the author. This project has the objective to use own developed Open Source RPAS that can be used to various applications, from aerial to terrestrial, like precision agriculture, heritage conservation, monitoring and 3D modeling, surveying, cadaster, among others. The Eye2Map project is evolving into a Startup business, already in incubation process in Science and Technology Park of University of Porto (UPTEC), an outcome from winning the European Satellite Navigation Competition, regional prize from Portugal, in October 2014.

Photogrammetric software is the most used tool for those kind of processing and, due to the preference for Open Source solutions, this study demonstrates the performance between software, analyzing and comparing important features like time spent, number of orientated images, data size, planimetric and altimetric precision and some qualitative comparison.

The learning and comprehension of the Open Source alternative in one of the major objectives during this study to better understand the workflow, pros and cons, and the possibility to use it in a professional environment.

Another objective was getting work experience with RPAS handling, both open source and commercial in different scenery.

The compared software were chosen from various options, and ultimately were PhotoScan [7], Pix4Dmapper [8] and MicMac [9], whose details are defined later in the photogrammetric software section and in practical work. The data were acquired in several study areas, surveyed by RPAS, with support from Real Time Kinematics (RTK) GNSS for ground control points and check points. Software features and similarities were compared and analyzed, including some hardware parallel between commercial and own developed.

Finally, Red Green and Blue (RGB) vs Near InfraRed Green and Blue (NGB) imagery is key to evaluate photogrammetric reconstruction variations, especially for precision agriculture applications.

1.3. Dissertation Structure

This dissertation is essentially divided in in five chapters, starting with chapter 1, composed by an introduction to the current situation and framework of RPAS development, applications and legislation, followed by the objectives for this study.

In chapter 2 extends the insight about the history of photogrammetry and focus even more over the RPAS technology, differentiating vehicles, the various sensors possible to be bundled with them and finally a description of some known photogrammetric software, followed by their respective comparison.

Chapter 3 represents the methodology adopted in each solution used and the portrayal of the study areas, including the first processing results, orthomosaics and DEM, for each area and software. Some experiments over hardware development are also available in this section.

In chapter 4, the in-depth analysis is presented, with statistics computed for each region of interest, checking output products by their positional error to ground truth, when possible. DEM are also compared to better understand the differences in model reconstruction by each solution, followed by another overall quality check, examining mosaic radiometric failures and building edges.

Finally, in chapter 5 there are the conclusion to this study, together with some critical review over the work, ending with some thoughts and proposition for future work and bibliographic references.

2. State of the Art

2.1. History of Photogrammetry

Photogrammetry, as we know it, dates back since the invention of photographic cameras in the nineteenth century, specifically when Nadar made aerial photography from a balloon in 1858, but earlier, Leonardo da Vinci contributed to understanding projective geometry from a graphical perspective. Another important development was introduced later with Johan Heinrich Lambert, in 1759, a name very well known in map projections. He introduced the mathematical principles of a perspective image using space resection to find a point in space from which a picture is made.

Over the years several improvements were made, pushing photogrammetry technology forward. The use of terrestrial photographs for topographic maps by Laussedat, removing lens distortion by Porro in 1865, introduction of airplanes and aerial photography by plane with Wilbur Wright, stereoscopy plotting instruments, just to name a few [10]. With computers, analytical processes began with solutions for camera calibration, orientations, bundle adjustment and other developments used in today modern photogrammetry.

Since 2000's, digital cameras were introduced to the market and changed completely the typical photogrammetry workflow. With digital photographs, computers are used to process all the data and produce geographical information without the need for expensive photo scanners used in analytical processes. Photogrammetry specialized companies use very expensive cameras, typically 1 million euros, with hundreds of megapixels, which ensures a very high precision, coupled with directed georeferencing using dual frequency GNSS receivers and Inertial Measurement Units (IMU) on board the survey plane.

Computer vision also contributed greatly to the advancements of this new digital photogrammetry, typically restricted to very few and used only with aerial data. In recent years, several algorithms were developed that were the foundation for newly broader photogrammetric software. Scale-Invariant Feature Transform (SIFT) was introduced by David Lowe in 1999 [11] principally to recognize objects between images with different image scale and lighting. The algorithm searches for key points in objects, usually the edges being the strongest, and then compare to the features of other images to select common points and identify the object. Other algorithms are also used in conjunction,

and for different applications, such as Random Sample Consensus (RANSAC) [12]. It's used to estimate parameters in mathematical models which contains outliers, useful to improve results from SIFT algorithm in object identification and tie point selection, upgrading upon the simple least squares method.

Officially named by the International Civil Aviation Organization as RPAS, these devices began to enter the photogrammetric business with great advantages and reduced operational costs. Compact cameras and other small sensors are used in those vehicles, achieving good precisions in the final products. Although they are not usually coupled with dual frequency GNSS receivers, with Ground Control Points (GCP) one can accomplish centimeter level precision in orthomosaics and Digital Elevation Models.

This new development brought the democratization of photogrammetry that was only available for professionals and very expensive. With drones, applications are also wider in offer such as surveying, precision agriculture with Near InfraRed (NIR) cameras, building three-dimensional (3D) modelling through terrestrial photogrammetry and structure movement's analysis.

The operation of RPAS in different kinds of surveying, using photogrammetry, has been studied and evaluated in the last few years with very positive results [13] [14]. These new data acquiring tools allow new methods and fields to be explored, from topographical coastal monitoring [15], to precision agriculture [16], heritage, city modelling and others.

2.2. Aerial Platforms

The earlier approaches to photogrammetry included hot air balloons, but with the first flight by the Wright brothers, manned aircraft established as the preferential platform for aerial. Even with digital technology, professional grade photogrammetry cameras are very expensive and can only be used with manned aircrafts, normally coupled with other sensors, such as differential GNSS and inertial sensors, in order to achieve direct georeferencing.

In the last few years there was a great new development in aerial platforms, the Unmanned Aerial Vehicles. Easy to use, fast and versatile, they quickly gained some market and are in rapid expansion in various kinds of applications. Knowing their pros and cons is fundamental to choose the correct vehicle to use, depending on the demand and location conditions.

Indeed, the Remotely Pilot Aircraft Systems were always developed with a military purpose in mind until very recently. Since the early 1900, there was an exploration and evolution of ballistic remotely piloted weapons like torpedoes and rockets, which removed the danger of being close to the enemy and without risking human lives from their side [17]. That same idea is what drives the current generation military drones like the famous Predator from the United States of America.

Although this kind of technology was developed in the 70's and 80's, in the sense of telemetry readings in ground stations and image streaming, only in recent years in the 2000's with the price of this technology brought down, people began to realize that RPAS could be used in numerous civil applications.

A huge number of new businesses started to appear and develop, pushing even further the RPAS technology and bringing them to the public use. One of the most profitable segments is the Land Surveying where companies like Sensefly, who leads the market with professional vehicles, easy and ready to operate and with excellent end results. Other companies that provide equipment to Land Surveying, like Trimble and Topcon, are also chasing this new business opportunity and more recently they introduced RTK into the equation, allowing to build and georeference models with centimeter precision, avoiding ground control points within the study area. For media applications companies like DJI is one of the most recognized due to the DJI Phantom model, so easy to use that they are even available for purchase in common electronics stores.

Equipped with this commercial surveying drones, several small businesses emerged in order to provide a great array of services in surveying, like monitoring agriculture and media. Particularly in agriculture, there is a vast number of possible applications with great interest and with the power to revolutionize agriculture. Given access to tools of precise agriculture at a small cost, producers and farmers in general could increase their production and decrease waste in resources.

In alternative to the commercial versions, several years ago, in 2007 an open source project was started, aiming to raise a community of developers and users of low cost RPAS. The ArduPilot Mega (APM) is the most used low cost flight controller and has an extensive documentation to guide everyone to understand and build homemade RPAS [18]. Currently progresses are being made every day with constant upgrades and debugging, helping this platform to grow even more stable and trustworthy, delivering solutions very close to commercial drones. A huge advantage in comparison to the former, is the ability to incorporate a wide range of sensors and even custom

modifications, giving some liberty of experimentation and creativity, easy to replace parts and the complete openness to everything.

In hardware there are two different platforms: APM and Pixhawk. The first is the most popular and since the beginning suffered some changes in design and specifications until it stabilized in the 2.6 version. Right now it's very limited in processing power, flash memory and dated sensors, and that's why is been dropped in support by the developing team when applied on multirotors. The complexity kept rising and flash memory was not enough, so Pixhawk came to replace the dated APM with powerful processing unit, new and upgraded sensors and more memory [19]. In firmware there are 3 different kinds, Plane, Copter and Rover, depending on which vehicle one wants to build and use. To control such vehicles, the supported software is Mission Planner [20] where waypoint navigation can be programmed, achieving autonomous missions, download mission log files and analyze them and the most important feature, configure all the electronic components of those vehicles.

2.2.1. Types of RPAS

2.2.1.1. Multirotor

Probably the best well known model is the multirotor, notorious for its multiple arms and motors. Quadcopters are the most common ones and they are even sold in electronic stores as toys. In fact, they are the most complex drone, as the multiple motors require some processing and level of synchronization in order to provide small adjustments to each motor individually depending on the drone action. This is definitely the most versatile vehicle, mainly because of its hovering capability and vertical takeoff.

The vertical takeoff is extremely useful in tight spaces, where could be difficult to land a bigger vehicle. With vertical movement and hovering, it's easy to apply terrestrial photogrammetry, especially in 3D modelling of buildings, like the one in Figure 1.Giving exact measurement with ease, even for hard to reach spots, could have major implications in Civil Engineering with building and structure monitoring [21].

Figure 1 –Three-dimensional representation of Leça do Balio Monastery

The major drawback is the flight time, because so many motors and other controlling electronics consume more energy. The weight/power balance is also a critical factor for the flight duration. Although there could be a very powerful and lightweight drone, the weight of the batteries can be a key issue for autonomy. Center of gravity, electronic interferences and wiring are also important factors to be supervised.

2.2.1.2. Fixed Wings

In the aero modeling universe, planes were always used as a hobby and without complicated electronics: either electric or combustion motors, speed controllers and radio receivers and transmitters. With the development of the open source flight controller, new horizons opened of what could be done with those same models, but with new and superior stabilization and navigation. And so, the fixed wings in RPAS were born, with the adaptation of the typical components in conjunction with an Arduino based flight controller and a GNSS receiver for automatic navigation. This is a big difference between the aero models and the fixed wings RPAS, the later can be controlled through radio or autonomously, guided by GNSS signals, while the models can only be controlled with a radio transmitter.

In this category there can also be considered another two, planes and wings. Wings are smaller in size and easier to travel with but due to the lack of a supporting tail, are more prone to destabilize in case of stronger winds and require more speed to hold itself in the air, being harder to wind sail.

The plane models are bigger in size, typically with detaching wings and even tail. Can hold longer flight times because of the wind sailing and requires less motor input to correct its path. Wings can have 30/40-minute flight time while planes can have a flight time of 1 hour and above. They are easier to launch in the air while the wings, usually the heavier ones, need a launching catapult or a strong elastic band to give them some kinetic energy in order to hold a steady flight.

These flight times are optimal for larger surveys, like entire cities, and very useful in precision agriculture for crop fields.

2.3. Sensors

Everyday there's new developments for sensors to be coupled with RPAS, as the list keeps growing and the applications are vast. Derived from remote sensing, several passive sensors were adapted and miniaturized to be flown by those vehicles. Multispectral and Thermal cameras are available in the market specifically for RPAS, while optical cameras are usually compact Point&Shoot or full frame Digital Single-Lens Reflex cameras (DSLR), depending on the vehicle payload and technical aspects such as pixel size and focal length. Hyperspectral cameras are also beginning to be commercialized with drones.

In the range of active sensors there are lasers, Synthetic Aperture Radars (SAR) and sonars. Laser can be used in two different kinds of application, the first is to measure the distance between the drone and the ground or an obstacle, the second is the laser scanning for creating dense point clouds. Short range sonars are also used in multicopters to provide distance to ground, in order the guide the landing.

SAR is also available for RPAS but requires larger payloads since they can weight from 2 up to 200kg [22].

IMU are an essential component in every vehicle because they provide yaw, pitch and roll corrections in their movement, achieving a stabilized flight.

The GNSS receivers provide location and navigation, a mandatory asset with this kind of technology. The most used receivers are single frequency code GNSS receivers from uBlox, available in mass to various electronics. Recently some RPAS manufactures

introduced to the market RTK solutions with dual frequency receivers on board. The environment of RPAS operation is the best for GNSS operation, without obstacles, allowing a constant stream of high quality information. This gives a huge advantage for ground level surveying and RTK removes the need for GCP while still achieving centimeter precision. Those receivers usually cost thousands of euros and are not available to hobbyist and small companies.

The alternative was introduced some years ago when Japanese researchers developed the RTKLIB software, an Open Source program package for GNSS processing [23]. At the same time, they started a study with low cost single frequency uBlox receivers that have access to raw carrier's phase data. Despite their limitation in frequency, with some initialization time, centimeter position can be achieved. The specifications of the antenna used were also import to achieve better results. That was the premise for startup companies to introduce low cost RTK solutions with possible integration with drones.

The first was Swift Navigation's Piksi receiver with raw carrier phase data access, which enabled RTK solution with a base and rover, connected to computers running RTKLIB, connected to whichever antenna desirable and broadcasting corrections from base to rover. From early stage, the company promised ArduPilot Mega integration but with little advances until know. At a price of 995$ for 2 receivers, 2 antennas and radio telemetry it was a cheaper alternative to survey grade RTK receivers.

Reach RTK from Emlid is a crowdfunded project in order to deliver the same proposition as Swift Navigation but now including survey grade antennas, which Japanese proved essential for better accuracy in positioning processing [24]. A pack with 2 receivers, 2 antennas and all the cables necessary costs 545$. Each receiver is built in a miniaturized computer, running a Linux distribution and processing carrier phase directly in each module using RTKLIB. A great advantage for immediate position calculation without the need to send the data over to an external computer. Those modules were also tested with ArduPilot Mega boards which ensures their compatibility and integration, accelerating the introduction of RTK solutions to the Open Source drone market.

2.4. Software

In this section it will be exposed and discussed some of the photogrammetry software available in the market, commercial and open source, comparing some of their

specifications, giving some insight of what was the reason for choosing certain applications instead of other. As nowadays precision and costs are extremely important, for professionals and academics, it's a great advantage to know exactly what are the strengths and limitations of each software in order to choose the best for different demands and applications.

2.4.1. Commercial Software

2.4.1.1. PhotoScan

Agisoft LLC is a Russian company based in Saint Petersburg that developed the photogrammetric software named PhotoScan. It is a multipurpose software for various kinds of photogrammetric processing of digital images, in order to deliver spatial data like orthomosaics, DEM or 3D modeling and visual effects. According to the company, the software was not based on existing open source photogrammetric libraries, and was developed from scratch [7].

The main workflow for this specific software is based in mainly 3 processing steps. The first is the alignment of photos where the software runs algorithms in order to select between images, matching points or tie points that gives relative orientation to the images in an arbitrary 3D coordinate system. This generates a sparse point cloud that allows a very early control check over the set of images. Camera calibration is also computed through this step, given the focal length, width and height of pictures, pixel size, projection center and distortions are calculated for each one.

The second phase is about building a dense point cloud, where based on the camera relative position, the software will calculate depth information and complete the previous sparse point cloud. Usually this generates millions of points, close to Light Detection and Ranging (LIDAR) data, and can be classified and edited in order to produce Digital Terrain Models (DTM), eliminating buildings and grove.

The final step is the construction of the 3D model where points from the dense point cloud are connected, building a mesh of polygons through triangulation algorithms.

This is the general approach to the PhotoScan workflow, whether the purpose is 3D modeling of objects or traditional aerial photography. For spatial data there are some tools like GCP placement and the export of orthomosaics and DEM, which are essential for this type of professional use. While in the case of 3D modeling other tools like creating masks and textured models, help the process.

2.4.1.2. Pix4Dmapper

Pix4Dmapper is the software developed by Pix4D company, based in Lausanne, Switzerland. It is sold as a specific RPAS mapping software, defining their target market as RPAS owners to produce spatial data and 3D modeling of buildings. Since this company has a key partnership with commercial RPAS Sensefly, each vehicle is bundled with their photogrammetric software. The modified software version, Postflight Terra 3D, is specific to work with that company.

The user has little control over the process, as the main goal is to reduce user input in the processing chain. After the RPAS flight, images are loaded to the software with the flight log, in order to georeference the photos by cross-referring the camera trigger position written in the log files. Then, one can choose to proceed into full processing and wait for the final results, orthomosaic and DEM. There are some editing tools for more advanced users, such as cloud editing, mosaic area and tie point and GCP marking.

2.4.2. Open Source Software

Several open source software are available for exploration and very recently new ones have emerged specially with RPAS projects like Ardupilot Mega that gives the general public tools and knowledge to build their own drones. Despite several commercial software available, they are very expensive to the common RPAS user and so, within the community, some software began to have some highlight in the photogrammetric processing.

The first ones to appear were VisualSFM, Bundler and later the Python Photogrammetry Toolbox, software for 3D modeling using structure from motion image technique [25]. In fact, this computer vision process, alongside other algorithms such as SIFT and RANSAC, are the basis for various other software, including commercial ones. Those are then used in conjunction with Multi-View Stereo codes to reconstruct 3D objects or scenes. Although they are very proficient in computer vision, is possible to achieve orthomosaics and DEM combining several software such as VisualSFM with CMVS, but they lack in georeferencing tools and spatial data creation.

Open Drone Map is another promising solution, but for now is only available in Linux operation systems and is based on Bundler. This last open source software was

already proved to be one of the photogrammetric solutions with more deviation in the 3D reconstruction, comparing to the ground truth [26].

Since 2005, the software MicMac was developed by Pierrot-Deseilligny while working in IGN, Institut National de L'Information Géographique et Forestière, integrating various scientific developments at the time, in order to produce DEM, image matching, 3D modeling, and others [27]. Over the years several others joined the team and worked to create a multipurpose software, able to process various kinds of information, from satellite images, RPAS photography, small objects modelling, multispectral imaging, just to name a few. This establishes MicMac as the most complete and reliable open source photogrammetry software available, with several occasional updates introducing new tools and developments to the toolchain. Some that are not even considered in commercial software like vignetting corrections, specific satellite toolbox and converters to other open source programs [28].

The main workflow in MicMac for aerial photogrammetry follows several steps, beginning with the tie point's calculation between each image. Next there is a camera calibration and bundle adjustment where cameras are placed in a relative position and corrected for distortions. If the images are geotagged, the relative model can be georeferenced using a local system, and then into the appropriate coordinate system. At that point, images are orthorectified and stitched together creating a final orthomosaic.

The main drawback from MicMac is the lack of a Graphical User Interface (GUI) that could help visualize the model while processing. The user can only export some results to other software between steps, in order to check upon the photogrammetry process. Opposing this difficulty, this is very trustful software with useful and diverse tools, developed by a public organization and now with help from CNES, Centre National d'Etudes Spatiales.

2.4.3. Software Comparison

Starting with MicMac, it's not friendly to new users, and some computer knowledge is required as everything is mainly processed from command line. There are some graphical interfaces, but sometimes generate errors and are not available for every tool. A complete photogrammetry workflow can be achieved with batch files, allowing a fully automatic processing.

Computer vision software is always very demanding in hardware resources and all these software are not exception. Especially with large data sets, above 200 photos,

they consume large amounts of memory and processing power. Another drawback for MicMac is the kind of processing. Instead of allocating data in memory, it writes everything into the hard drive, generating huge quantities of data. With commercial software, everything is placed in memory until the final results.

Both PhotoScan and Pix4Dmapper offer a friendly user interface, easy to use even for people without photogrammetry experience. On the other hand, MicMac requires some deep knowledge about the processes, and each step has many customization options for a very personalized result and depending on the type of work.

In the past, Pix4Dmapper offered a cloud based solution for everyone that would like to produce spatial data but couldn't do it, either for lack of computer resources or simply because a one-time license is too expensive. Nowadays, that option is no longer available, but the pricing is divided in 3 options: two rentals, monthly for €260 or yearly for €2600, and a one-time purchase license is also available for €6500. In PhotoScan the pricing has two options: a standard edition with limited functions for $179 and a professional version with all features, including the geographical information module, for $3499, both as a single lifetime license.

Obviously MicMac as a free and open source software, cost is not taken into account.

Table 1 – Features of each photogrammetric software

	PhotoScan		**Pix4Dmapper**	**MicMac**
Feature	*Professional*	*Standard*		
Photogrammetric triangulation	✓	✓	✓	✓
Dense Point Cloud	✓	✓	✓	✓
3D Model	✓	✓	✓	✓
Fisheye and spherical correction	✓	×	✓	✓
Dense Point Cloud Classification	✓	×	✓	×
DSM/DTM Export	✓	×	✓	✓
Orthomosaic Export	✓	×	✓	✓
Measurements	✓	×	✓	✓
GCP support	✓	×	✓	✓
Multispectral imagery processing	✓	×	✓	✓
Real Time Visualization	✓	✓	✓	×

In Table 1, MicMac only fails on the obvious lack of GUI and in point cloud classification. Although MicMac can measure distances through a specific GUI for GCP

input, areas and volumes cannot be measured, as opposed to the commercial alternatives. In this open source solution, the user need to export some products to other solutions in order to proceed those actions with areas and volumes.

Usually these software are compared by their technical precision in geolocation. From a business/client perspective, other features must be investigated, such as quality of the orthomosaic or DEM generated, evaluating building edges, noises introduced and overall mosaicking including radiometric equalization.

3. Methodology

3.1. Processing

This study will focus on the performance of the chosen photogrammetric software in different case studies. Different areas were chosen based on their location, difficulty, and heterogeneous nature. The final products, orthomosaics and digital elevation models are georeferenced in European Terrestrial Reference System 1989 (ETRS89) Portugal Transverse Mercator 2006 (PTTM06), European Petroleum Survey Group (EPSG) code number 3763, the official coordinate system in Portugal.

In every study area, those final products were compressed and cut into the same region of interest in order to have equal measurements in all solutions, using open source software QGIS and Geospatial Data Abstraction Library (GDAL). The time consumed and quantity of data are important measures to take into account to better understand what could be the best solution, combining time spent, data created and processing power required. The number of aligned photos was also recorded for each study area in order to identify changes in processing.

The flights were made by eBee from Sensefly company, a professional mapping drone property of University of Trás-os-Montes e Alto Douro (UTAD). The drone has a package, including travel case, the drone itself, onboard sensors and 2 software: a mission planning called eMotion, and another for photogrammetric use, Postflight Terra 3D, a variation of Pix4mapper, adapted to only process photos taken by Sensefly drones. Some of the specifications drone and the onboard cameras are detailed in Table 2. As it is a closed and proprietary system, the specific wavelengths covered by each band. Only that a typical RGB camera was modified with a NIR filter, removing the Red Band. The software is internally calibrated to operate with this specific filter, in order to build vegetation indices.

Table 2 – Specifications of the eBee RPAS and onboard sensor

Specifications	*eBee*	Specifications	*Onboard Sensor*
Weight	0,69kg	Company	Canon
Wingspan	96 cm	Model	IXUS 127 HS
Material	EPP	Weight	135g
Flight Time	50 min	Sensor type	RGB/NGB
Wind Resistance	12 m/s	Resolution	16.1 MP
Cruise Speed	11-25 m/s	Focal length	4mm
GSD	up to 1,5 cm	Trigger Type	USB

The photos taken by eBee are all georeferenced, with information about position in World Geodetic System 1984 (WGS84) and attitude in the Exif. These data allow meter precision georeferencing without GCP. All the data was processed in a custom built computer, located in FCUP with the specifications from Table 3.

Table 3 – Technical specifications of the computer used for processing

Processing Computer	
Hardware	Specifications
Processor	Intel i7 4820K 3,7GHz Quad Core
Motherboard	Asus P9X79
Memory	8x Kingston CL9 8Gb DDR3 1600 MHz
Graphics board	Asus GeForce GTX980 4Gb GDDR5
Hard Drive	SSD 500 Gb + HHD 4Tb

For each solution, two different workflows were followed, for processing with and without GCP. And so, in PhotoScan without GCP, the steps to follow are quite simple and the experience with the software was always easy to understand. Some useful data can even be exported, like camera calibrations, camera positions and others. First, the user only has to upload the photos to be processed and then take three steps: Align Photos, where camera calibration and tie points will be calculated based on image and location if the images are georeferenced; Build Dense Cloud, from which will be built a dense point cloud based on a sparse point cloud from the alignment step; and finally Build Mesh, joining the dense point cloud into a mesh of polygons. Then the user only has to export the Orthophoto and DEM into the desired coordinate system.

The workflow with GCP is quite similar, with control points being imported from a text file into PhotoScan and placed into their associated position in each photo. After that, the tool Optimize, calculates and adjusts camera external and internal parameters as well as other distortions. Then, dense point cloud and mesh are again built to generate the final results.

In Postflight Terra 3D the experience was even easier as little user input has to be done. Without GCP, the output coordinate system is chosen and, after uploading the photos, there is only local processing where orthomosaic and DEM are calculated. To input GCP, only initial processing is needed, where tie points and camera calibration are calculated. Then, control points are positioned into their respective place for each image and optimized for every point. The remainder of processing is followed, achieving the final results. The user experience of this software, is that it was design to be operated by everyone without prior knowledge about photogrammetry. Technical names are changed

simply into processing, and little options are given about exporting products, other than dense point cloud, in contrast with PhotoScan were even the chain of commands identifies what will be done at each step. Pix4Dmapper also generates a final report, with lots of technical information, very well design, simple and professional. But in the end is the most limited and constrained photogrammetric software.

For MicMac the processing takes a lot more steps, requires deeper knowledge, but also gives much more control over the end result. Even with the manual, some tools are not well explained, while others are not documented at all. The process of understanding how it works was very hard with lots of experimentation, testing and reading throughout the software forum. The user community is also very small, which means that help is not always easy to access. The first experimentations were done by sample data provided by IGN and user community, located in a File Transfer Protocol (FTP) server, and were key in understanding the basic steps, as example commands were included with the samples. Talking with some users, Maria João Henriques from LNEC (Laboratório Nacional de Engenharia Civil) and Luc Girod (one of MicMac's developers) also helped clearing out some doubts and allowed a deeper understanding.

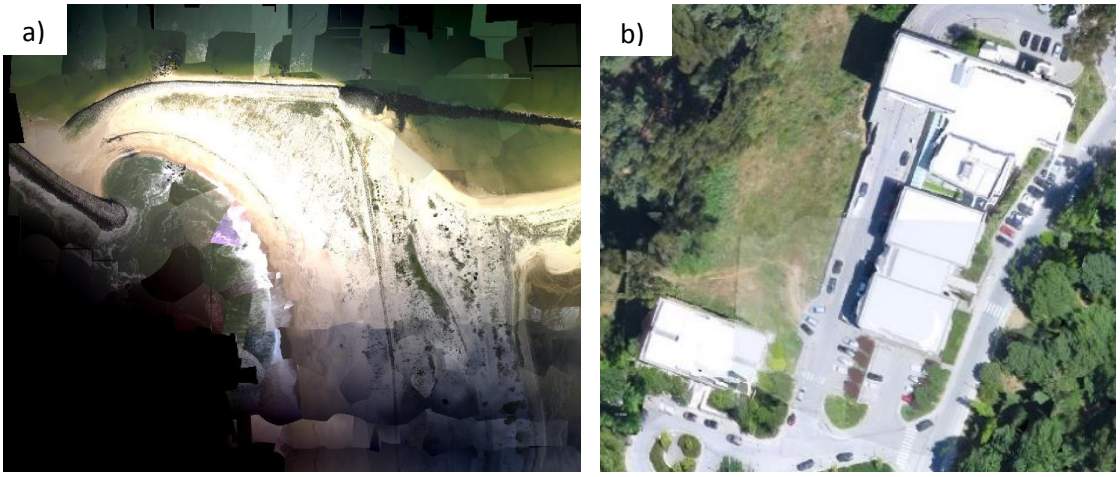


Figure 2 – Radiometric equalization difficulties in a) and building reconstruction issues in b)

Thus was possible to almost achieve the final results, but were still lacking in quality, with very bad radiometric equalization and not well defined building limits like the results in Figure 2. More testing was needed and at this point it meant tweaking minor parameters within each different function to generate huge variations in results, mainly in the final two steps, in DEM and orthomosaic creation. Scene structure complexity, number of images per feature, correlation between points, degree of equalization and sample size, were some of the parameters that required more attention and dedication

in order to achieve the best results possible. This kind of customization is very useful, but in this initial experimental phase, meant a lot of time wasted as some parameters could take the program to run during several days, extending up to a full week, delaying the understanding of MicMac.

Other kind of information like camera calibration, orientations, error analysis, etc., is present within MicMac and it is possible to export but many time the tools required failed or were too complex to operate and understand.

Towards the end of processing all the data, another setback occurred. The final altimetric output from MicMac was displayed in number of pixels instead of elevation per pixel. It was not clear at first that an auxiliary file was generated with the altimetry GSD and origin. Multiplying the output with the GSD and adding the altimetric origin produced the expected DEM. This procedure was not obvious and held back some of the work.

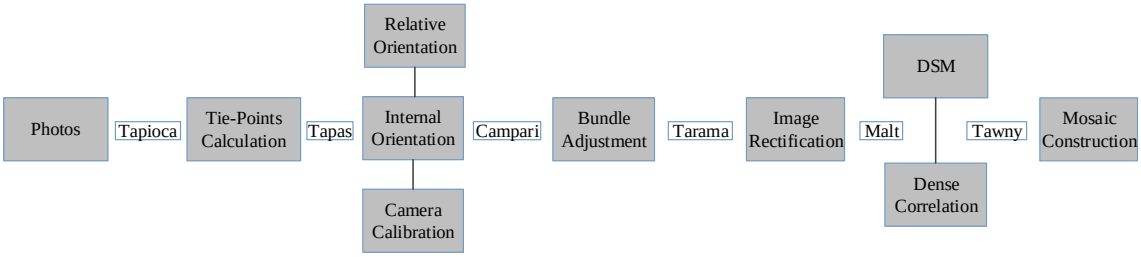


Figure 3 – Simplified Workflow with MicMac's functions and results of each step.

The chain of command starts with the geotagged photos, their position must be translated into MicMac language, typically Extensible Markup Files Language (XML) files. Exiftool, also a powerful open source software, is used to export GNSS information from every image into a text file. Later, that text file is read by OriConvert in order to calculate an initial orientation in a local coordinate system and choose which images, based on their location, could be coupled. It creates a XML file, with possible image couples that are used in Tapioca, a script that calculates Tie Points between images. The next step is the camera calibration and relative orientation, achieved with Tapas with different distortion models available. The model used in this workflow is Fraser model as it is the Photogrammetric Standard Model, containing a radial model with affine and decentric parameters, with 12 degrees of freedom. Successive calls from Tapas also work to achieve smaller errors, especially in larger data sets where it could not converge to a good solution. It is advised to compute orientation in a small set of images and later apply another calibration, with the later as an input.

This orientation can be visualized using AperiCloud, which creates a sparse point cloud from the oriented images with their respective position in a 3D space with arbitrary coordinates. With CenterBascule that orientation is then georeferenced in the local system calculated previously in OriConvert. It is also changed into the desired final coordinate system with ChgSysCo, a program only for coordinate transformation that allows for proj.4 syntax in XML files. The images are then transformed into epipolar imagens with Tarama and then Malt creates the Digital Surface Model (DSM) and dense point cloud. The final step is done with Tawny which basically merges all orthorectified images for each photo into a single orthomosaic with some radiometric correction options.

3.2. Data Sets and Results

3.2.1. First Area: UTAD

As the drone used for data acquisition is property of UTAD, the first obvious case study is the University campus. It's located in Vila Real, in the outskirts of the city, and has an approximate area of 300 hectares with several 3 floor department buildings, agriculture occupation and botanical gardens, as the main study fields of the University are Agriculture, Forestry and Veterinarian applications. Therefore, this is the ideal start due to the proximity and nature of the area, allowing for a classification of mixed urban and rural.

The flight was done on the 3rd of June 2015 with a targeted ground sampling distance of 10 cm for the orthomosaic, translating in a 300 meter above starting point altitude flight, with corresponding flight plan on Figure 4. The pixel size was chosen by combining the total area coverage in a single flight with operational time from the battery. In total, 114 photographs were taken in RGB and 113 in NIR imagery with the same planning, with around 20-minute flight. Near Infrared Imagery was also acquired because it is intended to pursue studies with vegetation indices within the campus. It is also important to notice changes in processing between RGB and NIR imagery. The 7 GCP, represented by green in Figure 5, were collected by differential GNSS and post processed by the University prior to this study, while 5 check points for planimetric and altimetric analysis were collected the day after the flight, in red, and finally 10 points were later measured in the orthomosaic for further relative analysis, in yellow. Most of those points were collected in sewers covers that are easy to identify. Figure 6, Figure 7,

Figure 8, Figure 9, Figure 10 and Figure 11 represent both orthomosaics with corresponding histogram and DSM, produced by each software in RGB. Figure 12, Figure 13, Figure 14, Figure 15, Figure 16 and Figure 17 represent the same data, but with NIR imagery.

Figure 4 – eBee's flight plan over UTAD

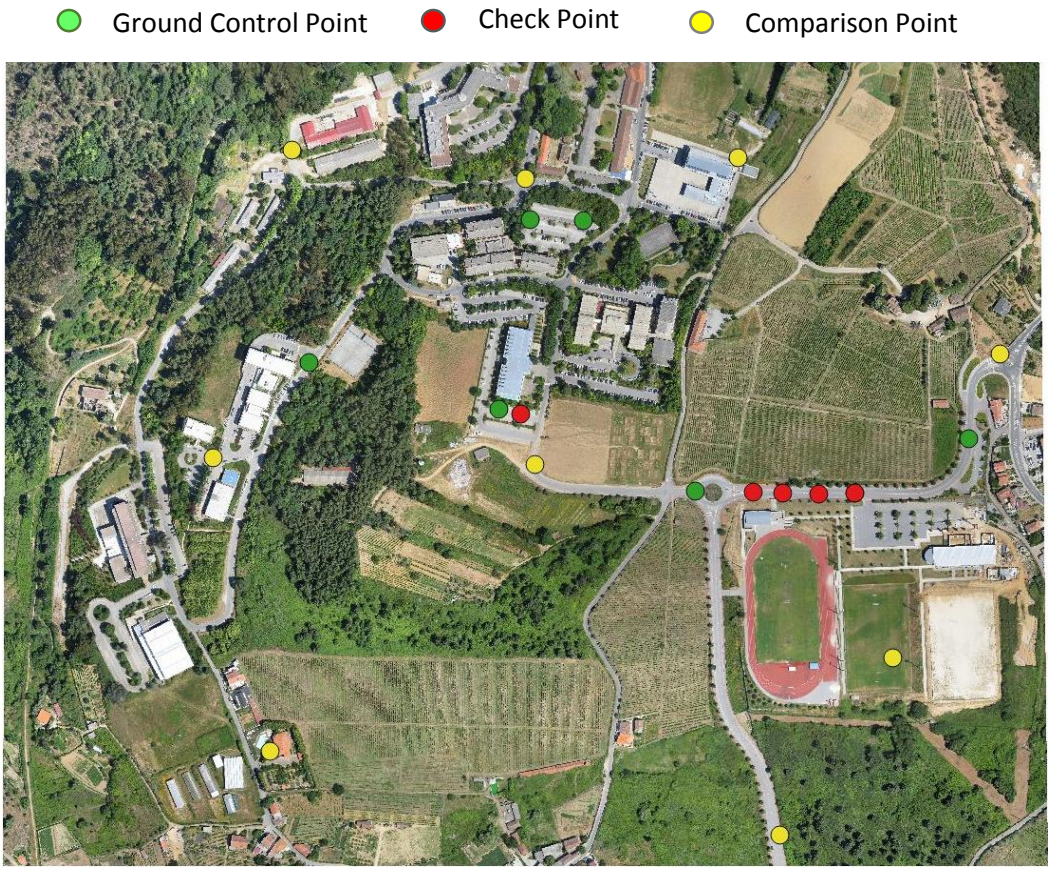


Figure 5 – Representation of the all the points used for analysis in UTAD

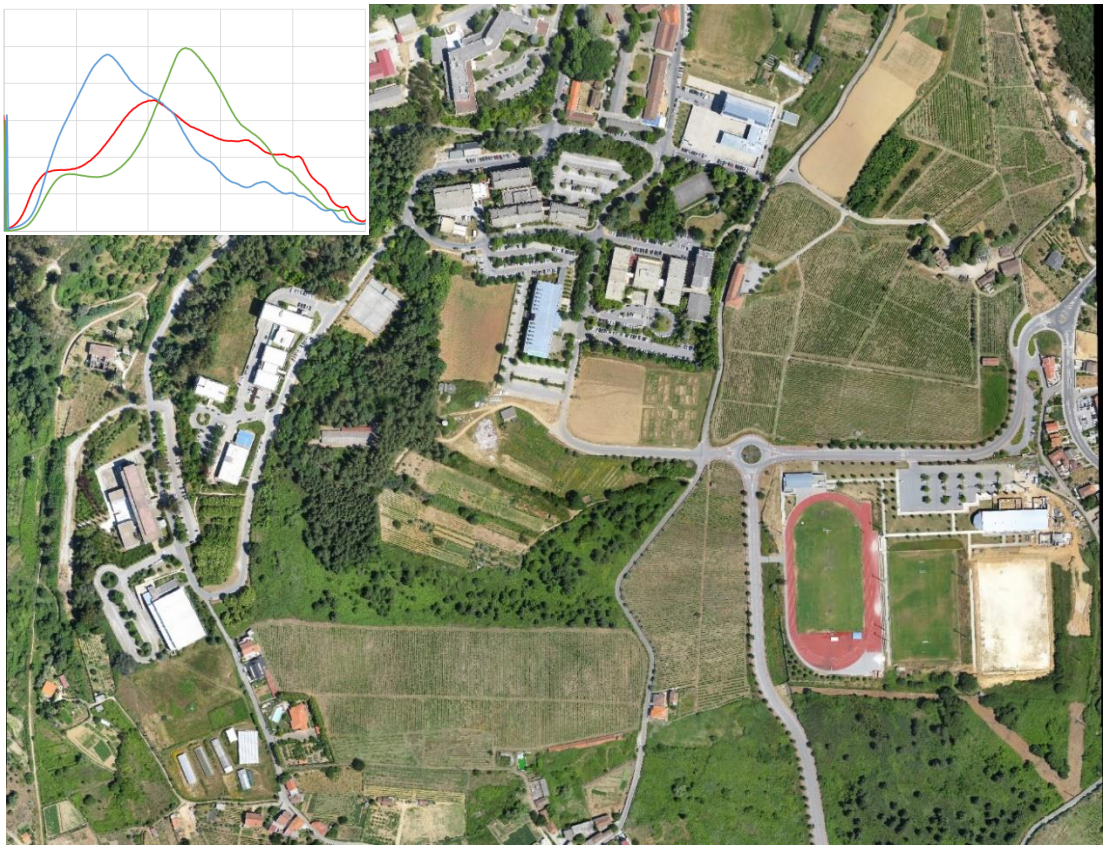


Figure 6 – Histogram and orthomosaic of UTAD, processed by PhotoScan, with GCP

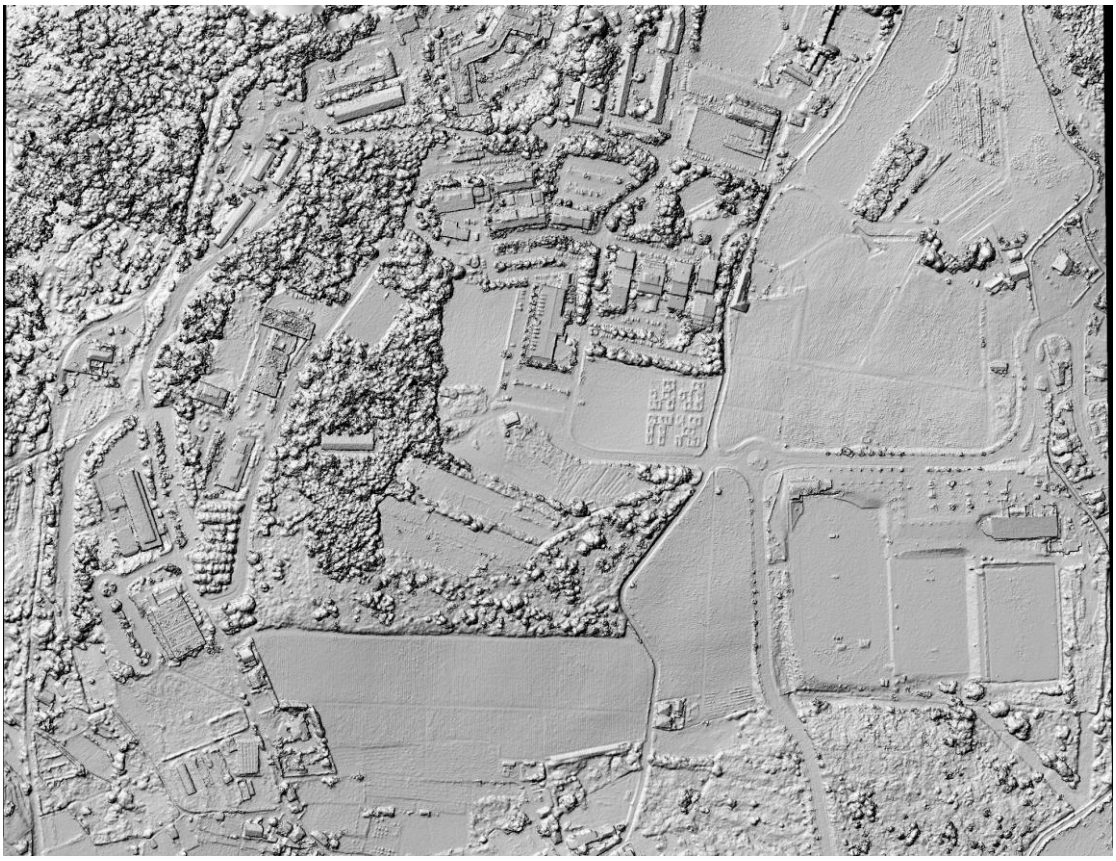


Figure 7 – DEM of UTAD, processed by PhotoScan, with GCP

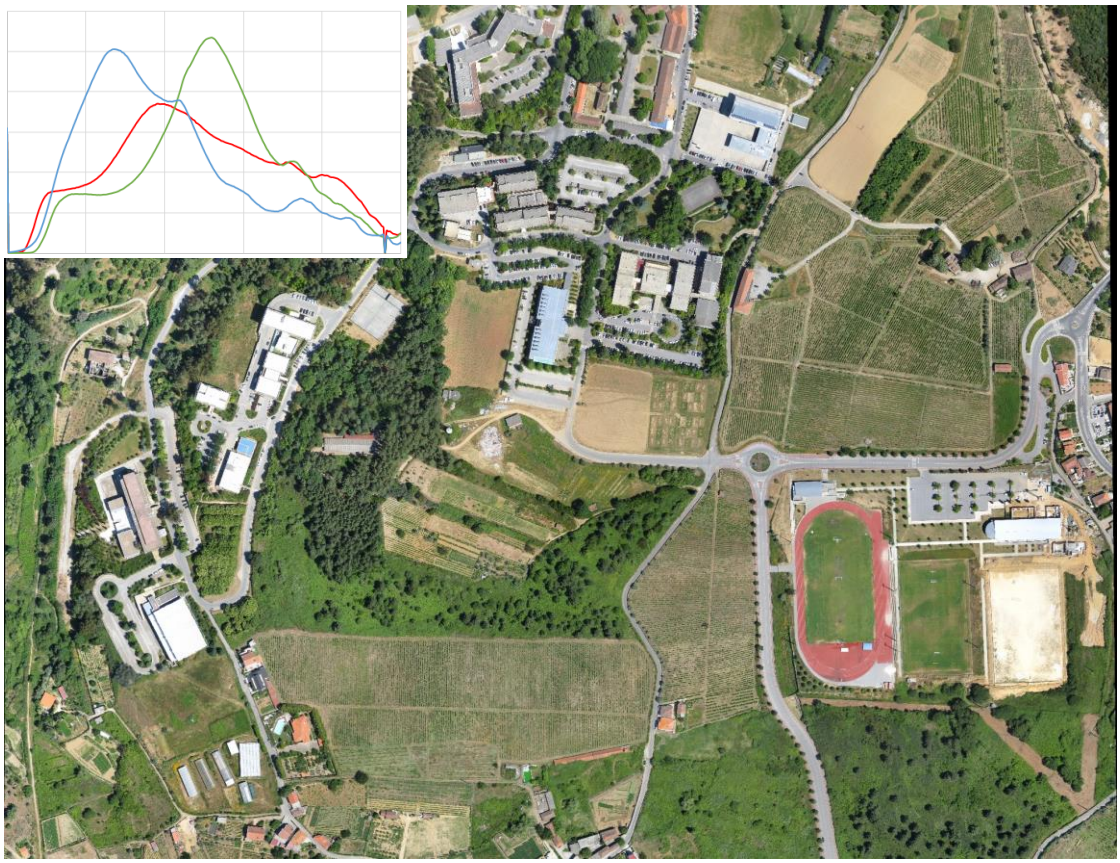


Figure 8 – Histogram and orthomosaic of UTAD, processed by Pix4Dmapper with GCP

Figure 9 – DEM of UTAD, processed by Pix4Dmapper with GCP

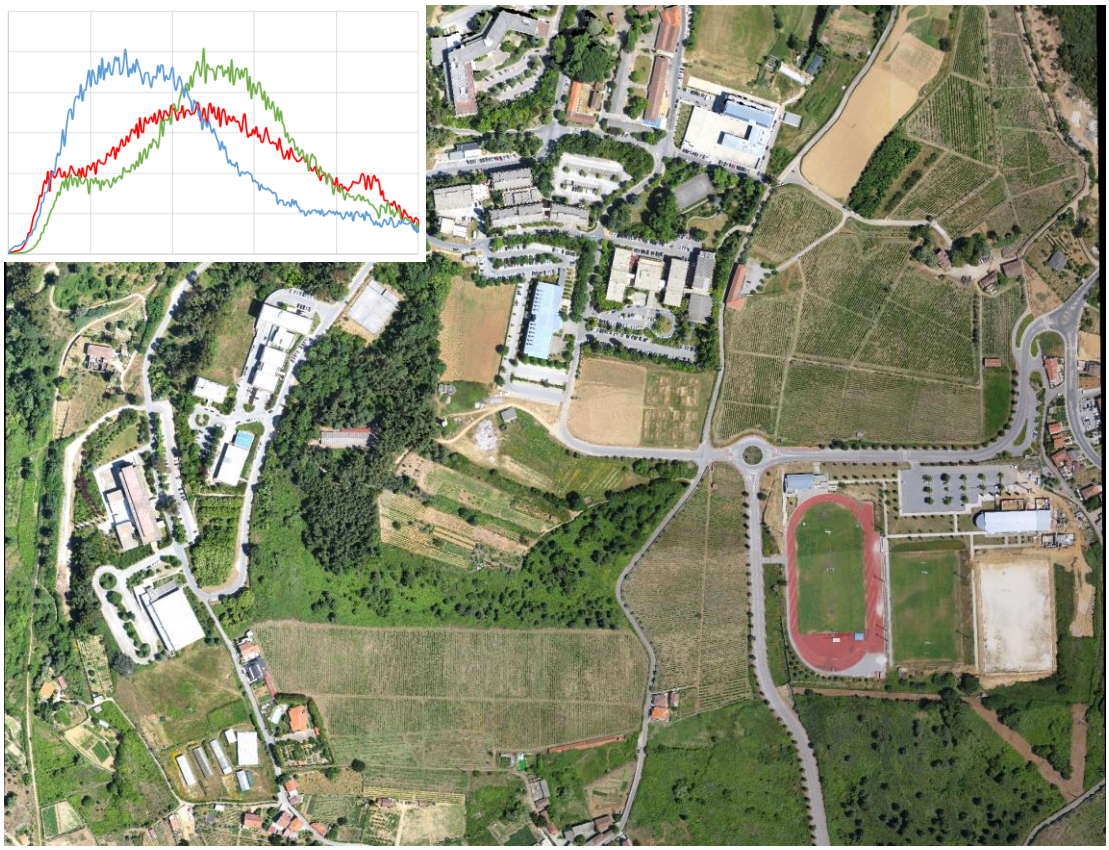


Figure 10 – Histogram and orthomosaic of UTAD, processed by MicMac with GCP

Figure 11 – DEM of UTAD, processed by MicMac with GCP

Visually the orthomosaics seem to be very similar, especially from the commercial solutions where the results are almost identical, confirmed by the histogram of each image having the same signature. Although in MicMac the histogram appears to be different, in fact, the values are almost the same but with some irregularity resulting from internal image algorithms. In the orthomosaic is also noticeable a few cuts in color, mainly in field areas where the homogenization was not done properly.

The model's shaded relief from commercial software show visually almost identical results. The main difference comes from MicMac where grove was largely eliminated, while small sized vegetation (vineyards and other agricultural fields) and sparse trees maintained its structure. This output can be controlled with parameters in MicMac, resulting in a good solution to be applied in remote detection for agriculture, whereas in the other solutions these vegetal formations are eliminated. For this study only the typical (basic) workflow was used.

When the main interest of the processing is to obtain Digital Terrain Models, MicMac offers a variety of parameters that can be used to specifically eliminate tall vegetation. Since the other solutions workflow are linear, only the final product can be edit to produce a DTM, but MicMac's toolchain can be altered and personalized, presenting a great advantage compared to others. Tweaking parameters such as image correlation to force the matching, and regularization parameter due to the high irregularity in canopy structures.

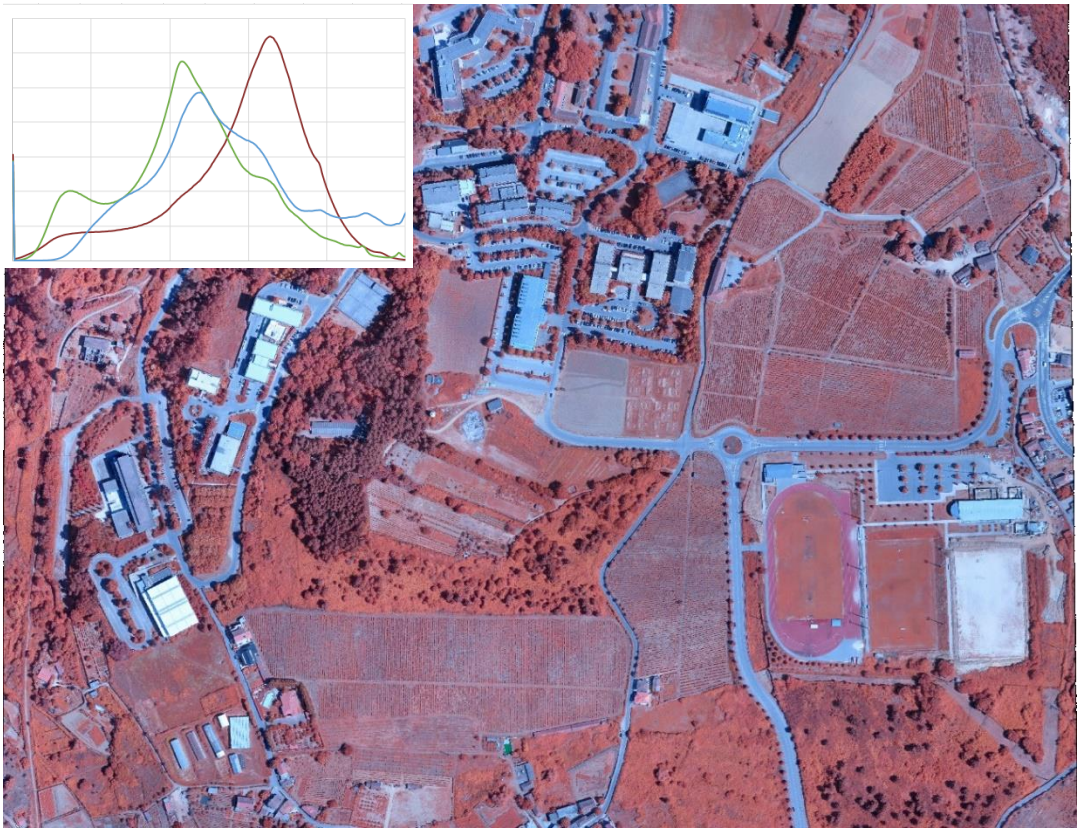


Figure 12 – Orthomosaic of UTAD's NIR imagery, processed by Photoscan, with GCP

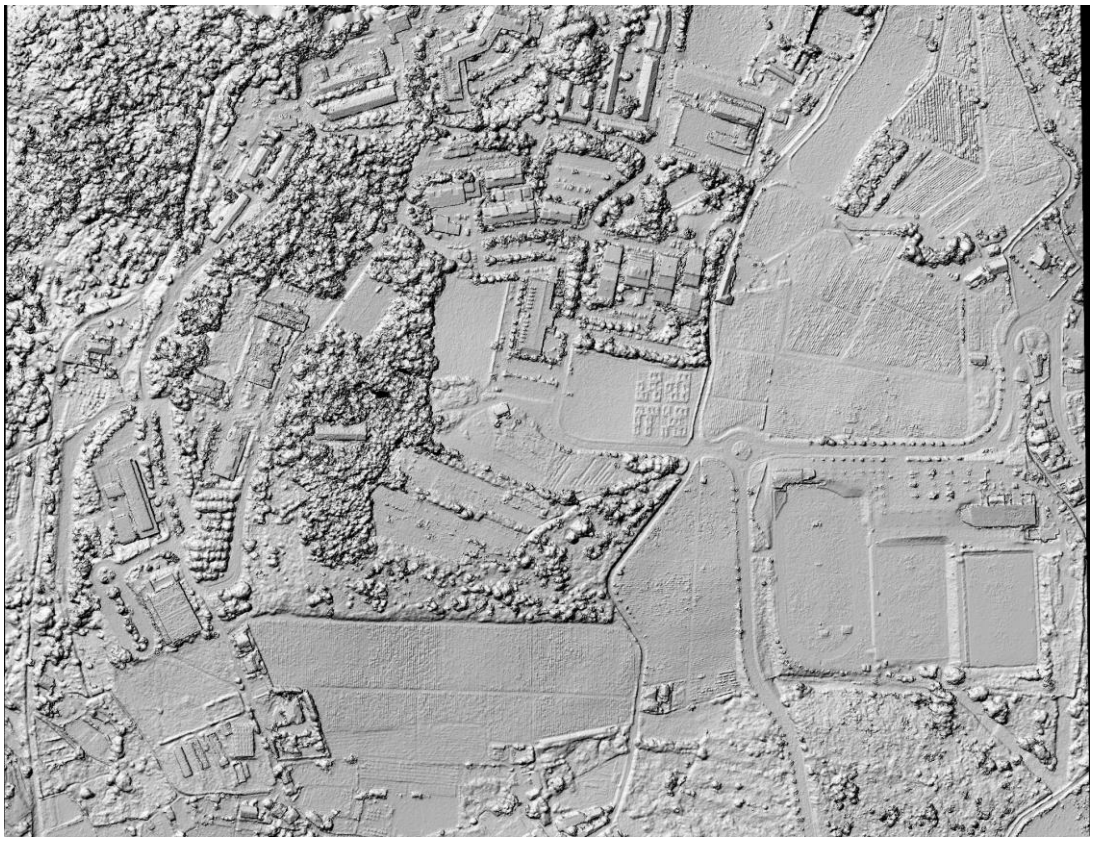


Figure 13 – DEM of UTAD's NIR imagery, processed by Photoscan, with GCP

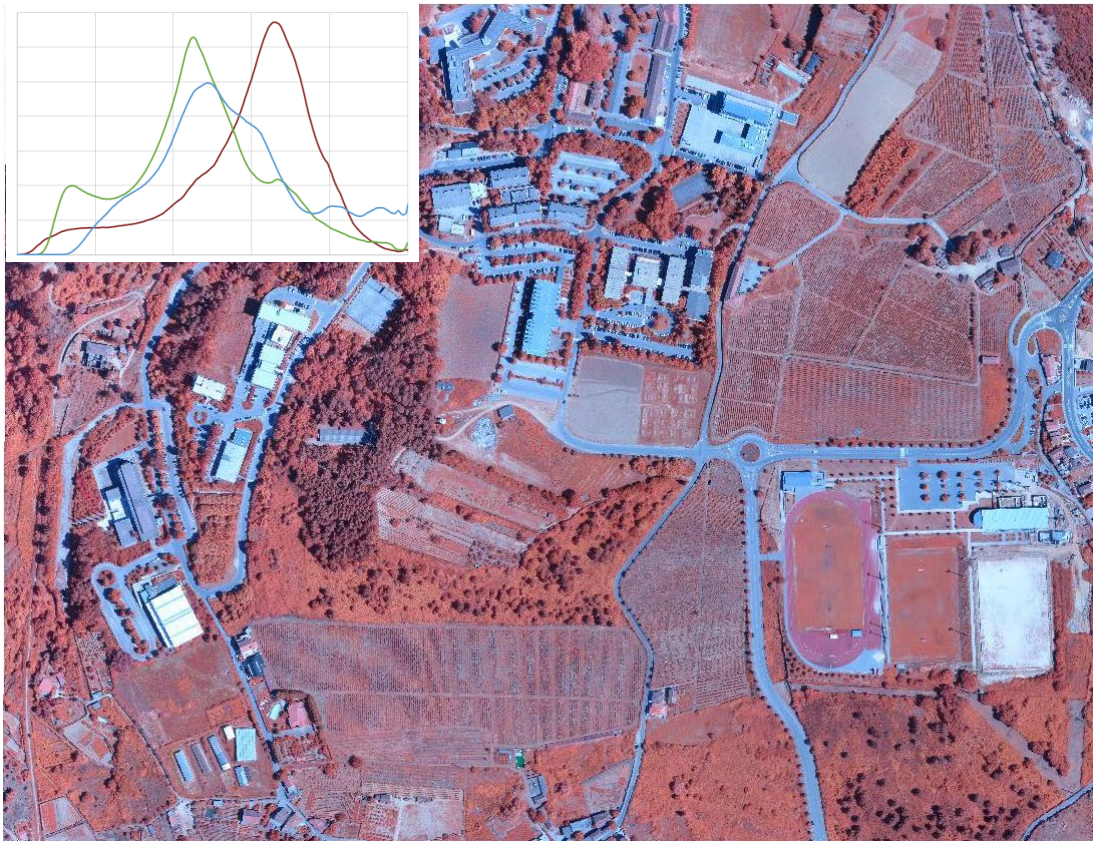


Figure 14 – Orthomosaic of UTAD's NIR imagery, processed by Pix4Dmapper, with GCP

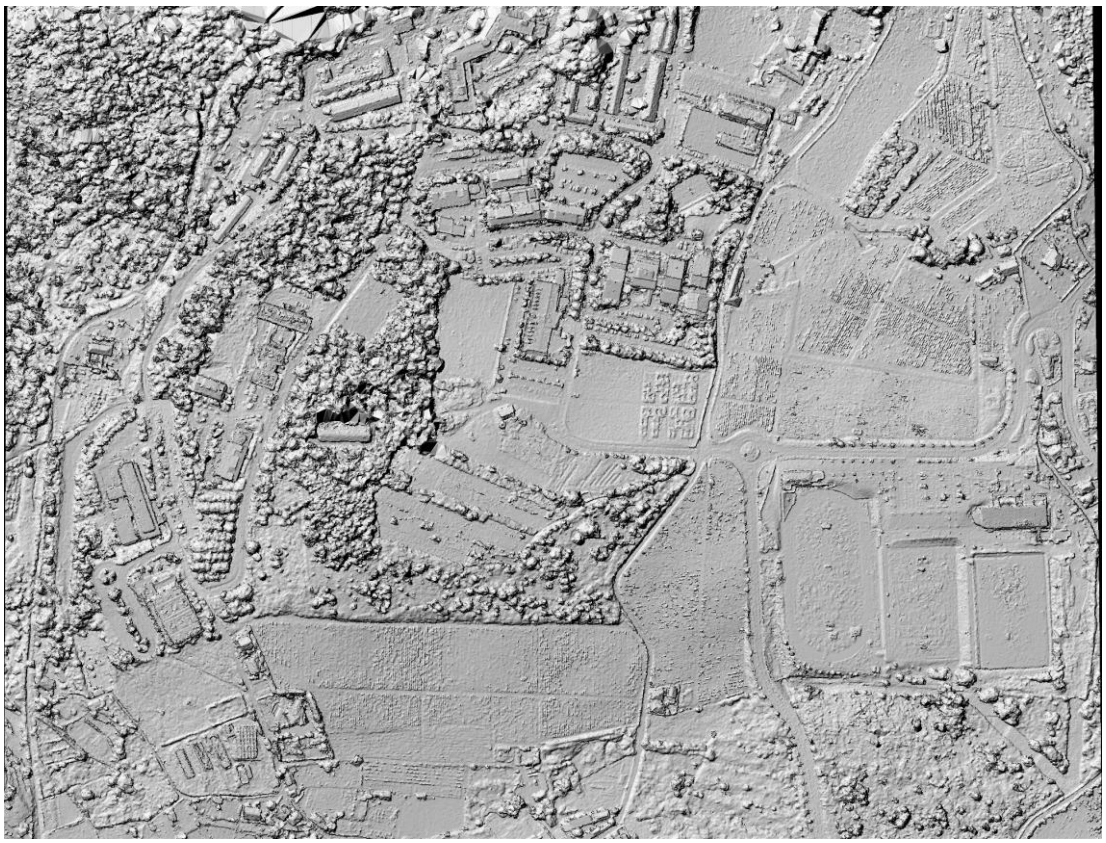


Figure 15 – DEM of UTAD's NIR imagery, processed by Pix4Dmapper, with GCP

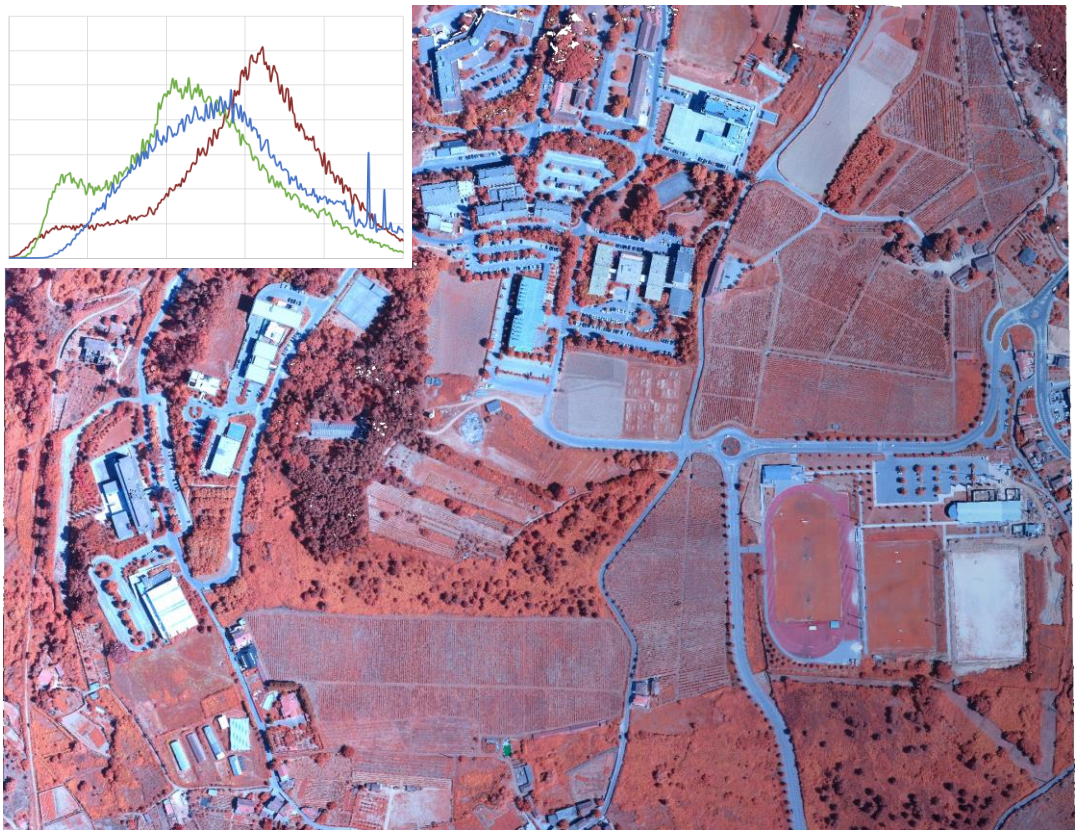


Figure 16 – Orthomosaic of UTAD's NIR imagery, processed by MicMac, with GCP

Figure 17 – DEM of UTAD's NIR imagery, processed by MicMac, with GCP

The results obtained from Near Infrared imagery are identical to the RGB ones, with both commercial solutions outputting visually the same result and similar histograms. Again MicMac has irregular values, already explained previously, and some rough cuts are still noticeable, despite being fewer than in RGB results.

The models produced seem to be influenced by the wavelength used, as short vegetation started to appear in Pix4Dmapper and even introduced some errors in flat fields, like in the university sports fields. PhotoScan is the least affected by this different imagery, being the most noticeable difference the prominence of vineyards. As seen with the RGB model, the NIR model in MicMac maintains the vineyard structures all over the area, and also presents more grove.

3.2.2. Second: Douro River Sandspit

Portugal as a country with a huge extension of coastal zones, it is of great importance to monitor and map certain areas, susceptible of morphological changes due to the rivers and sea cycles over the years, zones where millions of euros are spent every year helping to protect the population from sea advancement. One of those high importance areas is the Douro River Sandspit in Lavadores, as it has been studied in the last years with investigators from FCUP. The presence of water in photographs can also lead to errors in image matching algorithms due to the lack of common points and homogeneity between followed images.

The flight was done on the 6th of May 2015 with a target ground sampling distance of 5 cm, the best resolution possible considering the area and flight time, corresponding to a 160-meter height. The area flown was approximately 95 hectares in a 23-minute flight, acquiring 242 images. Wind conditions are usually critical in this location but that day were optimal, with less than 5 m/s winds, but still noticeable in some strips represented in Figure 18. Six GCP (green dots) and another six check points (red dots) were collected at the time of flight using GNSS RTK with some artificial markers built for this surveying, because no natural markers exist in the study area. Their locations are represented in Figure 19, and the following Figure 20, Figure 21, Figure 22, Figure 23, Figure 24 and Figure 25 represent the orthomosaic with corresponding histogram and DSM.

Figure 18 – eBee's flight plan over Douro River Sandspit

Figure 19 – Representation of the all the points used for analysis at Douro River Sandspit

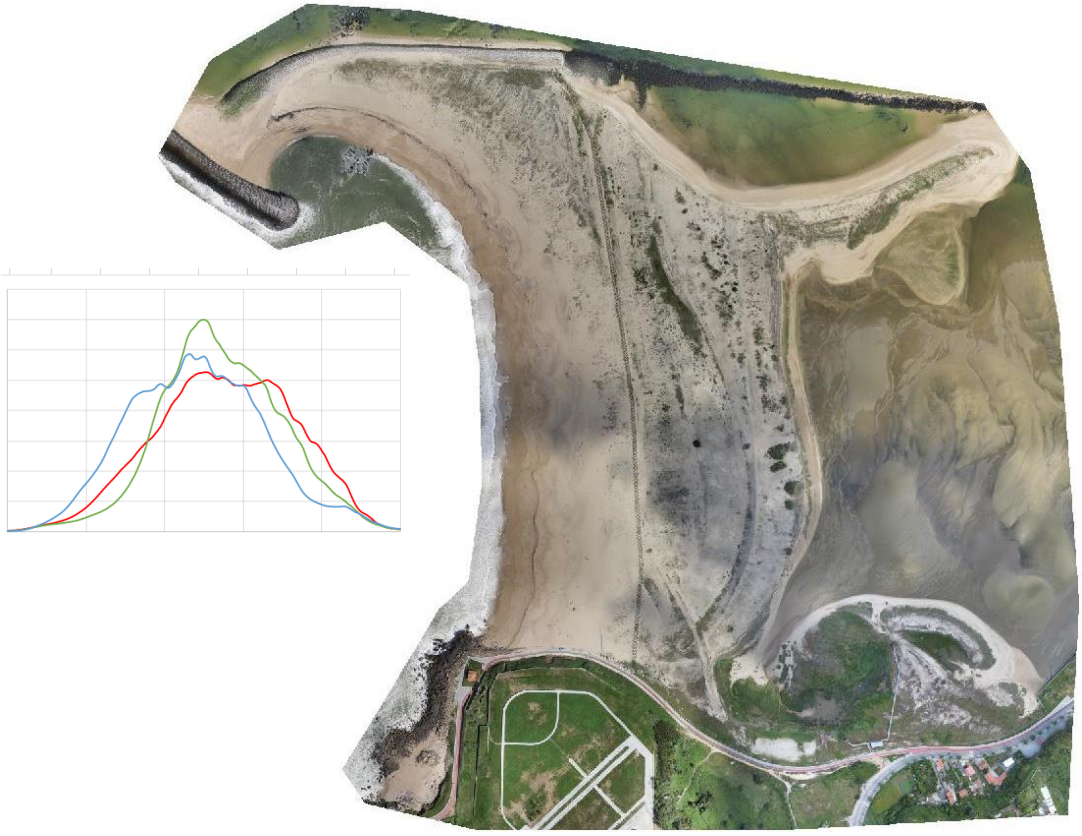


Figure 20 – Orthomosaic of Douro River Sandspit, processed by Photoscan with GCP

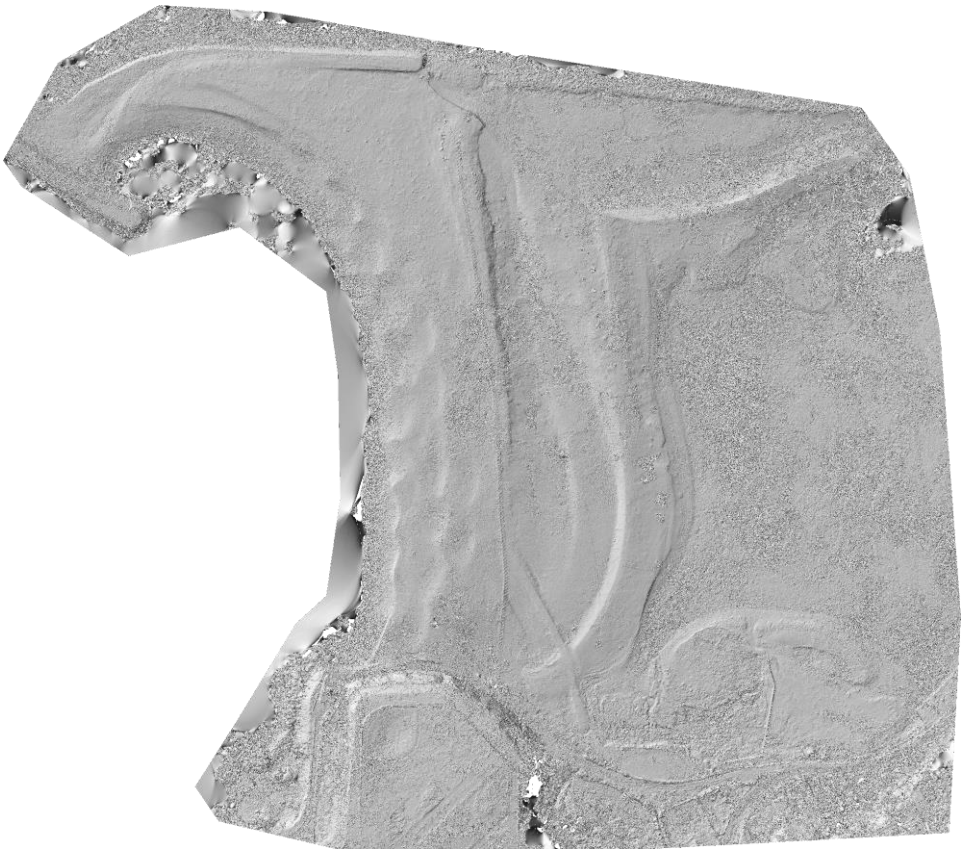


Figure 21 – DEM of Douro River Sandspit, processed by PhotoScan with GCP

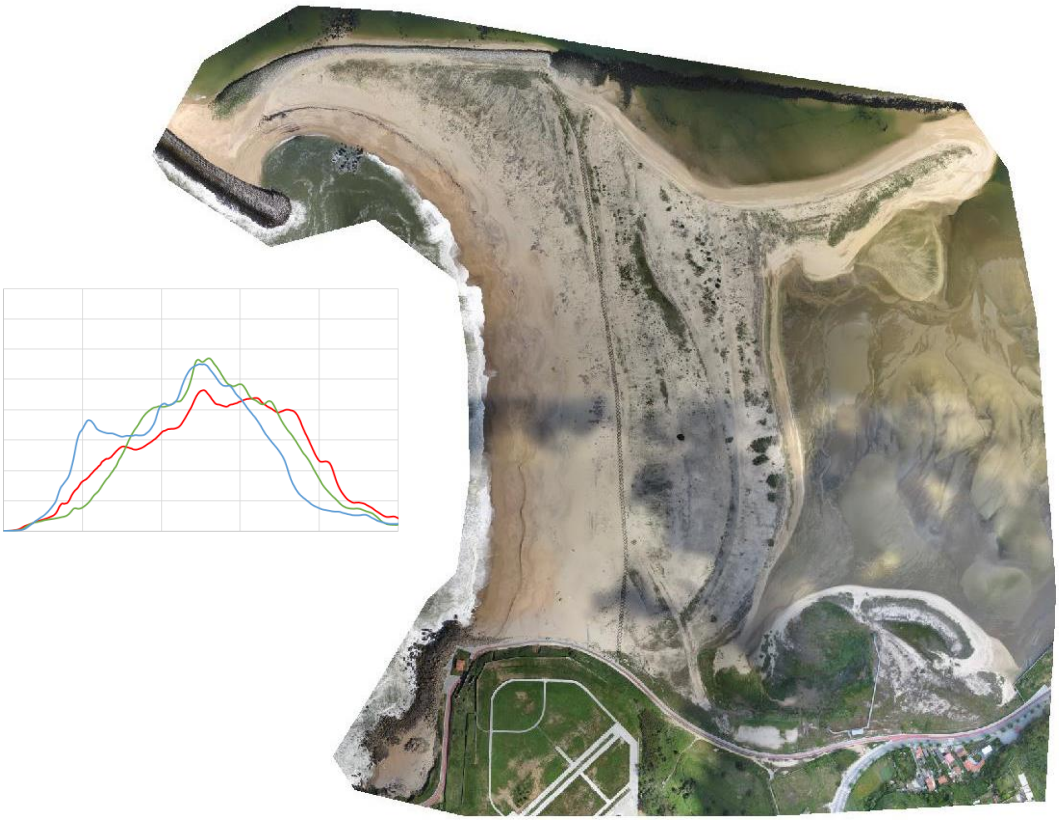


Figure 22 – Orthomosaic of Douro River Sandspit, processed by Pix4Dmapper with GCP

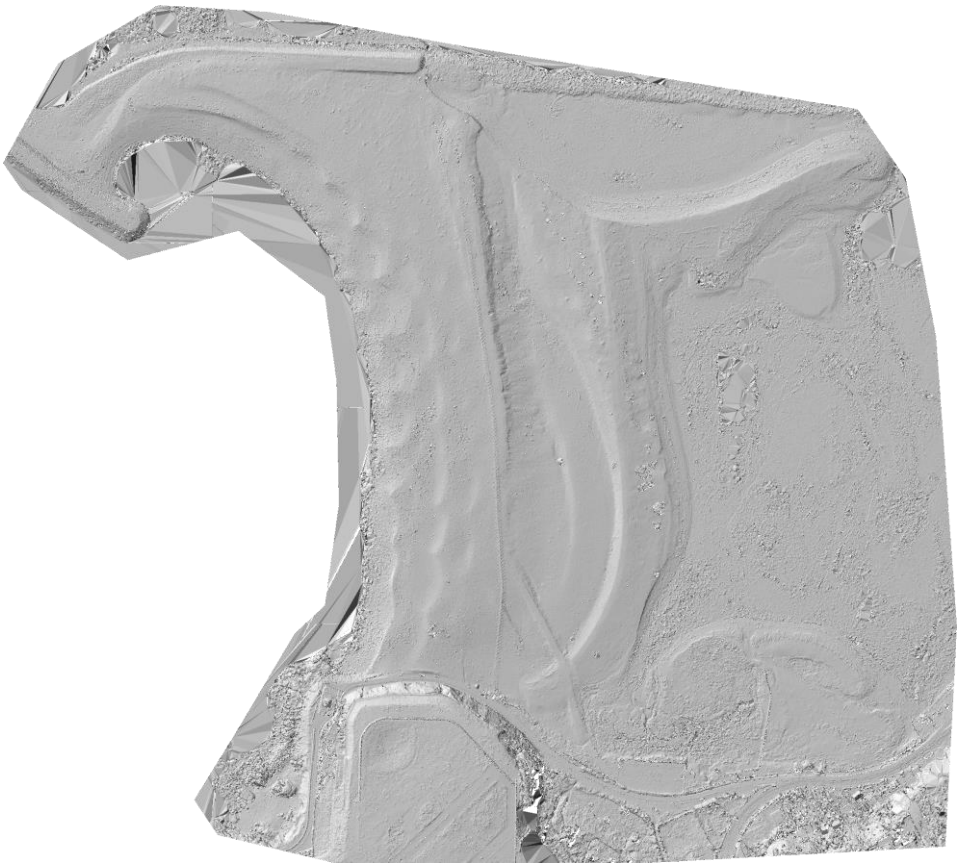


Figure 23 – DEM of Douro River Sandspit, processed by Pix4Dmapper with GCP

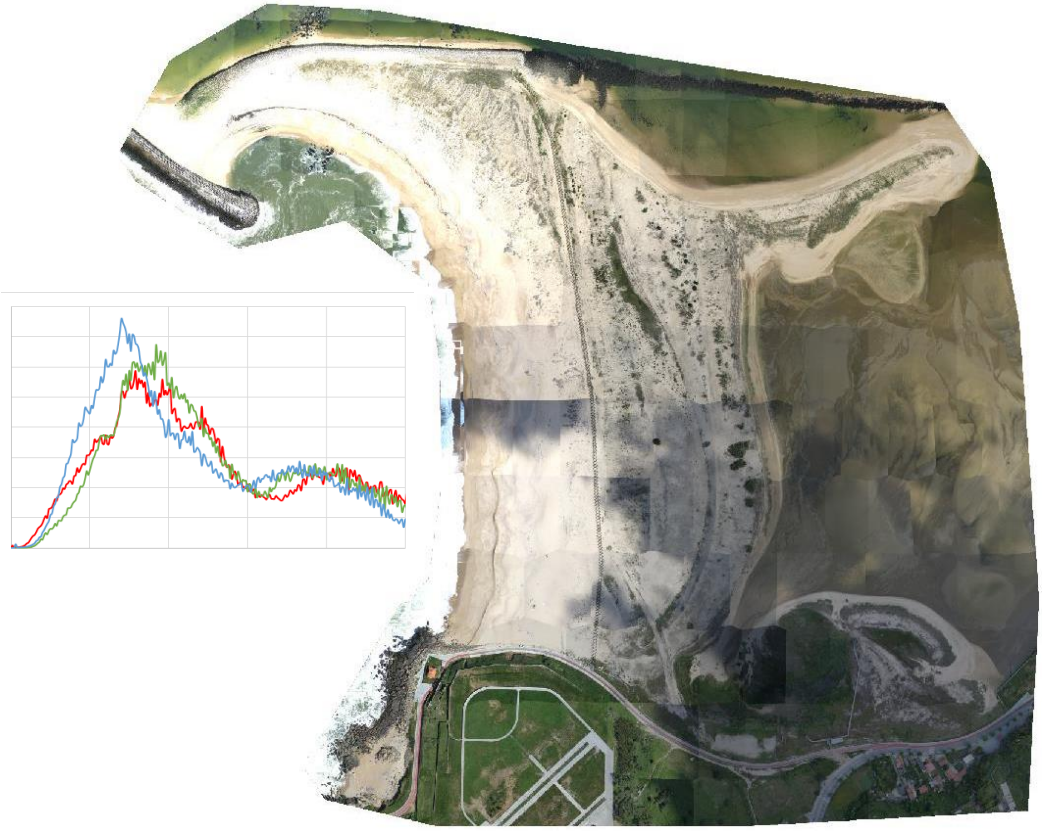


Figure 24 – Orthomosaic of Douro River Sandspit, processed by MicMac with GCP

Figure 25 – DEM of Douro River Sandspit, processed by MicMac with GCP

The light conditions on the day of the flight were poor, switching between sunlight and cloudy, leading to problematic lighting in individual photos which will affect further in the processing. Some photos were overexposed (Figure 26) while others had some dark shadows from clouds.

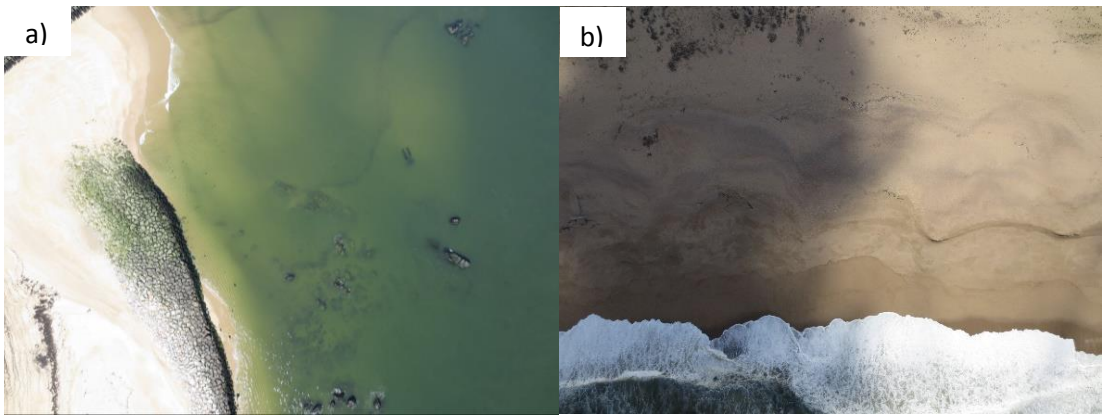


Figure 26 – Examples of overexposure (a) and shadows (b) present on the photos

In MicMac both effects are present in the final orthomosaic, introducing even more difficulties in radiometric homogenization, which is already a weak point from this software. On the other hand, PhotoScan and Pix4dmapper produced good final products with fine radiometric equalization, even more in the first case, where cloud shadows seem to be more faded than the later. The saturation and brighter image are also confirmed by MicMac's histogram, with many values near high digital number for each visible band, unlike PhotoScan and Pix4Dmapper, presenting a good distribution of intensities like a Gaussian distribution.

At first glance, Pix4Dmapper and MicMac's models present similar sand surface, while Photoscan results have some noise, mostly on the central part of the image.

3.2.3. Third: Aguda

Related to the former area, in Aguda beach there was an intervention for the removal of sand deposited in a bay where local fishermen's boats used to harbor. The sand deposition created a barrier, making it impossible for the fishermen to return in to the sea.

Because of those morphological changes, it is of utmost importance to monitor these coastal areas and evaluate the need for action, helping reduce costs of unnecessary intervention and increasing the preemptive monitoring.

This area can be classified as a mix of urban and coastal, due to the presence of several building from the local town, but not as tall as in a major city, composed with mostly 2 floor housing.

The flight occurred on the 26th of May, 2013, for a monitoring project of Aguda beach, surveying a total area of approximately 50 hectares at a mean sea level altitude of 100 meters. This flight was executed by another Sensefly model with a Canon IXUS 220HS, a Swinglet, an older vehicle from that company but with same flight characteristics. The data was provided by other researchers, resulting in a 26-minute flight, with 150 photos, aiming at 5cm GSD for the Orthomosaic and 10cm for the DSM. As the flight have already been made, there was no access to the log file, therefore a Google Earth snapshot was used to portrait the data acquisition (Figure 27). Eleven GCP were collected at the time, distributed over the sand area and are represented in green in Figure 28. Yellow dots represent ten comparison points for relative analysis and green dots represent GCP. On this case there were no planimetric check points collected as it was not the objective do perform that study. Figure 29, Figure 30, Figure 31, Figure 32, Figure 33 and Figure 34 represent orthomosaics with corresponding histogram and DSM.

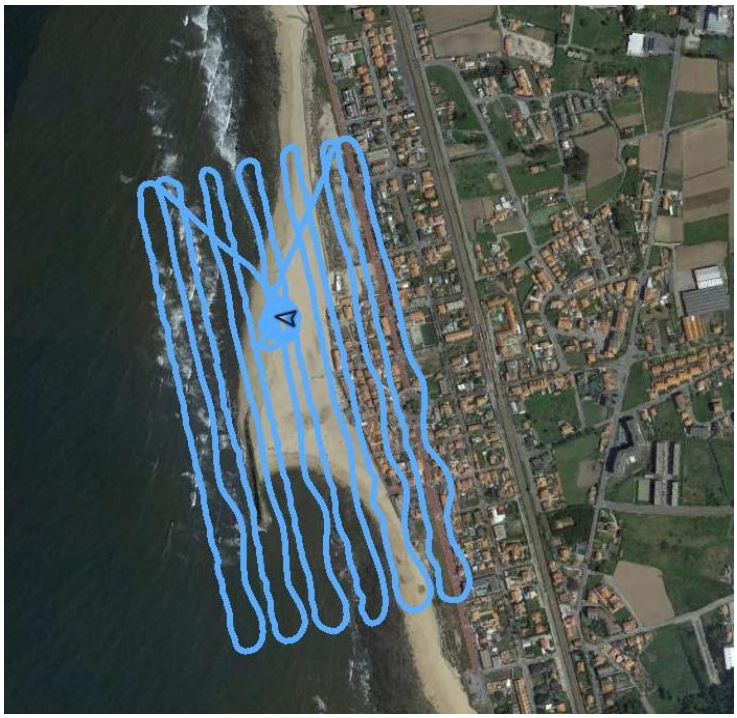


Figure 27 – eBee's flight plan over Douro River Aguda

Figure 28 – Representation of the all the points used for analysis at Aguda

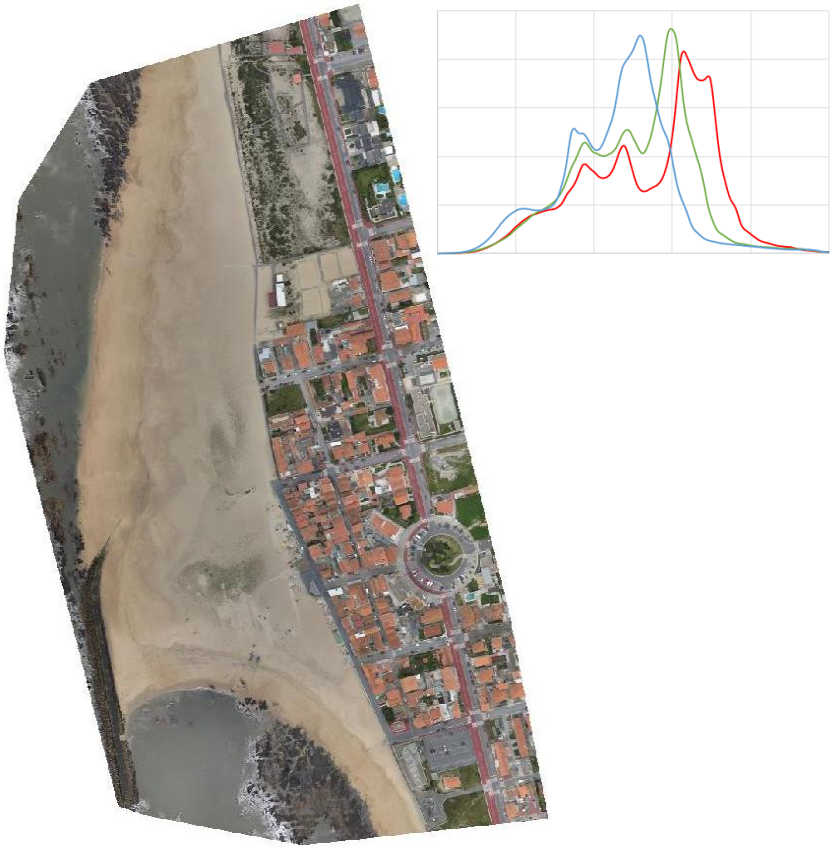


Figure 29 – Orthomosaic of Aguda, processed by PhotoScan with GCP

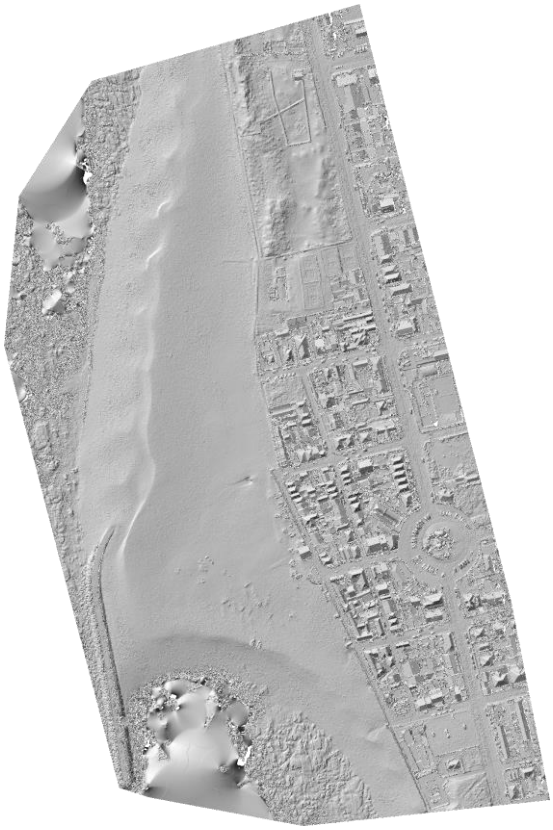


Figure 30 – DEM of Aguda, processed by PhotoScan with GCP

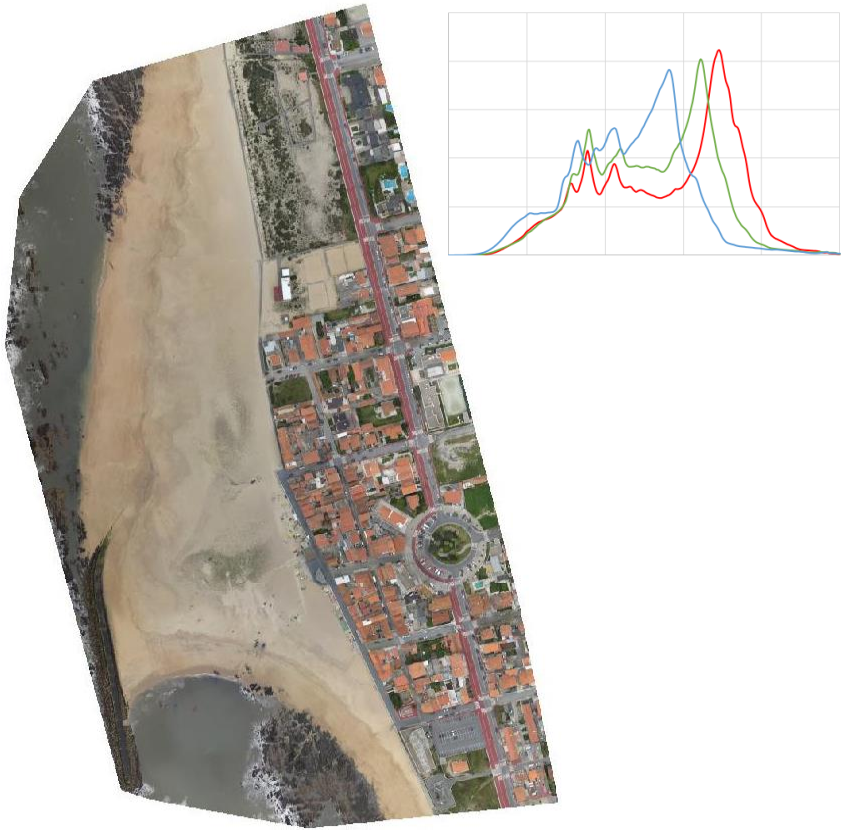


Figure 31 – Orthomosaic of Aguda, processed by Pix4Dmapper with GCP

Figure 32 – DEM of Aguda, processed by Pix4Dmapper with GCP

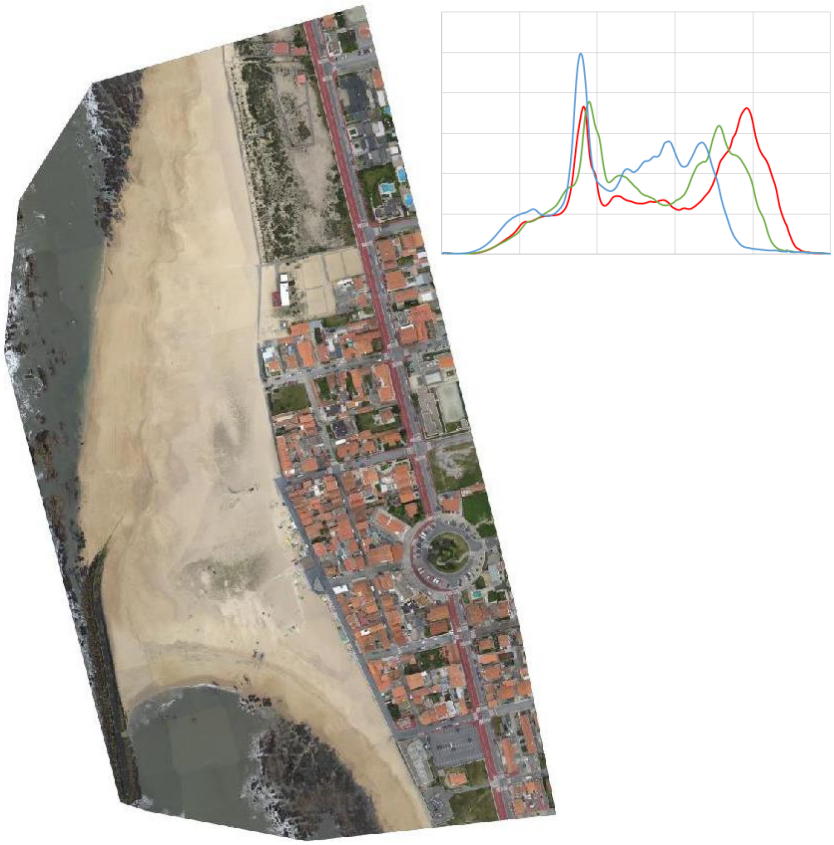


Figure 33 – Orthomosaic of Aguda, processed by MicMac with GCP

Figure 34 – DEM of Aguda, processed by MicMac with GCP

In this mixed scene of coastal area with sand and small buildings, the commercial applications dealt perfectly with orthomosaic generation, proved by the general aspect of said product and the balanced histogram produced by both software with more tendency toward higher values due to the sand. MicMac has problematic radiometric equalization in sea areas and in some sand zones. The histogram representation points higher dark values in the images from a darker urban area than in the commercial solutions.

Elevation models are also very similar except for some noise on the sand and also on buildings in Pix4Dmapper in the upper right region along the edge and more noticeable in MicMac. This could be a natural occurrence due to lack of overlapping images and therefore a worse 3D reconstruction. The flight path taken by the RPAS also gives some information about possible errors due to deviation of the vehicle by wind gusts. The commercial solutions, especially PhotoScan handled well this problem on the region of interest. MicMac introduced a large deal of noise in the zones near water, particularly in the breakwater and in the seashore.

3.3. Processing Metrics Comparison

By the end of processing, the number of aligned photos was recorded, as well as the final data generated (images, auxiliary data, and final products) and the time spent to process each study area. The number of aligned photos is important to better understand the differences in matching algorithms, to observe which could be using optimized versions of SIFT to extract as many features as possible but within a reasonable amount of time. Those recording are described in Table 4.

Table 4 – Amount of data, time and number of pictures aligned, for each software

UTAD			
Software	PhotoScan	Pix4Dmapper	MicMac
Data (Gb)	3,5	5	40
Time (hours)	1 - 2	2 - 3	10 - 12
Aligned Photos	114/114	114/114	114/114
Douro River Sandspit			
Software	PhotoScan	Pix4Dmapper	MicMac
Data (Gb)	5	8	75
Time (hours)	2 - 3	3 - 4	16 - 20
Aligned Photos	202/242	202/242	203/242

Aguda			
Software	PhotoScan	Pix4Dmapper	MicMac
Data (Gb)	2,5	3,5	30
Time (hours)	1 - 2	2 - 3	6 - 8
Aligned Photos	127/150	127/150	118/150

Again, the commercial solutions are very similar in time and data produced, with a small advantage for PhotoScan, for taking lesser time. However, in MicMac there are huge variances, taking longer processing times and out of proportion data volume. In fact, a disadvantage in this Open Source solution is the direct writing of data into the local hard drive instead of virtual memory, like the commercial ones do. The outcome is an inferior consumption of computer memory, where most of the information is allocated during processing in PhotoScan and Pix4Dmapper.

The time taken by MicMac in processing can be explained with the chosen configurations in order to achieve an extremely detailed elevation model and the tie point detection is proved to be far superior in number, when compared with other photogrammetric software [26]. The process of image matching can be accelerated with lower resolution images, reducing the processing and time needed to find key features in images with less pixels.

Another drawback is the manual selection of individual photos, where MicMac was not able to find matches, because it cannot continue unless all images, in the working, directory have matches. It's necessary to firstly run the program, just to identify photos with no matches, and remove those tagged images in order to continue.

The number of pictures has impact in time consumption and data produced as it is the case in Douro River's Sandspit, but at the same time, is dependent on the scene. The Aguda area had more photos than UTAD, but the time and data were inferior. The presence of water in some images, resulted in alignment failure of coastal areas, and the not so complex scene and homogeneity of the sand beaches is the key of the speed up of processing, resulting in less time spent and data.

3.4. Hardware

At the same time, during the practical work, it was assembled an Open Source RPAS, for professional use, for the project Eye2Map. The goal for that vehicle would be comparing its performance against a commercial alternative with huge market share and reliability.

Unfortunately, the assembly was delayed over time, because of several drawbacks. After acquiring the foam structure, the electronic components placement inside the frame wasn't perfectly arranged, which caused the plane to be unstable. Some modifications were also made to the foam, including a placement of optical filters in order to protect the camera during landing, and also to enable the possibility to couple other filters like polarized ones, which eliminates sunlight reflexes in photographs over water.

Later there were several testing over flight controlling parameters and the weight of battery vs time of flight, to achieve the best relation. Another important feature that was needed was the camera shutter control by the electronic flight board, in order to take pictures equally spaced, according to the overlap chosen for each surveying. This task was also one of the most difficult one, as it demands camera firmware modifications on several compact cameras and lots of flight testing, to achieve the best combination of internal camera configuration. The final model of the vehicle is presented on the Figure 35.

Figure 35 – EyeMapper by Eye2Map

Finally, battery endurance and flight modes were tested to get the final parameters for the adjustments.

A direct comparison was not performed between this model, the “EyeMapper”, and eBee from Sensefly, but some features can be confronted in the Table 5.

Table 5 – eBee and EyeMapper specifications

Specifications	*eBee*	*EyeMapper*
Weight	0,69kg	1,3kg to 1,8kg
Wingspan	96 cm	190 cm
Material	EPP	EPO
Flight Time	50 min	40-60+ min
Wind Resistance	12 m/s	18 m/s
Cruise Speed	11-25 m/s	11-25 m/s
GSD	up to 1,5 cm	No limit

Obviously the EyeMapper has a larger wingspan as it is a different kind of vehicle, a fixed wing, while eBee is a flying wing, with no tail support. This feature allows eBee to fly an equal amount of time as the other model, and with a smaller battery, thus a lighter weight.

The materials are almost the same, both being polymers. EPP in this case has a low density, making the structure even more lightweight, while EPO is cheaper and higher in density. This feature is a con as the higher density is more prone to leave small impact marks or even with normal handling, thus giving a worn look to the structure.

Flight time and GSD in EyeMapper are variable because in this model there is some liberty to change the battery. For now, is only flying with 5.000 mAh, achieving a 40-minute flight. The weight capacity allows to change the battery to a single 10.000 mAh or even two parallel 5.000 mAh, maxing the total battery capacity and weight. The GSD is a feature somewhat locked in Sensefly because they limit the minimum flight altitude and the RPAS can only fly with a specific camera. EyeMapper, on the other hand, being Open Source there is no limit to flight altitude and the camera model can range from several available in market, able to shoot by interval or by flight controller trigger, ultimately enabling, virtually, any GSD.

The complex nature of the fixed wing structure is ideal to withstand wind gust up to 18 m/s, while eBee is severely affected by strong winds.

Obviously a key difference between models is the money they cost, with Sensefly charging €20.000+ for a system comprised by case, telemetry, vehicle, flight manager and processing software. The EyeMapper model was purchased piece by piece, assembled by a team with RPAS knowledge and the priced ascended to €500. This is

only the cost of materials, without adding the time spent building and testing, but ultimately it's far cheaper than the other commercial vehicle used.

For the business team, the ultimate factor to choose the Open Source RPAS, besides price, is the liberty to perform custom modifications to its vehicles and the liberty to adapt any kind of sensors, being optical, infrared, laser, etc., something that commercial application don't allow and are extremely expensive when they do.

4. Comparative Study

The main goal of this study is to evaluate the performance and precision of each solution in the various scenes and to do so, ground control and verification points were measured. After processing and having all the final data ready (orthomosaics and DEM with same georeferencing and clipped by region of interest), several analyses were accomplished in order to evaluate them in quantitative and qualitative terms. Firstly, a relative comparison was made, to ensure that all software produce similar results and to identify some discrepancies between each other.

The most significant analysis is the absolute comparison with the verification points that gives the true ground positioning, allowing the possibility to calculate the differences in planimetric and altimetric position on the final products.

Precision Georeferencing is essential in most cases but general RPAS users may not have access to high precision GNSS for GCP placement. Another interesting aspect is the measure of error committed when no ground control points are used during processing. Some application may not use GCP for processing and the GNSS georeference from photos may suffice, thus it is of some importance to analyze the difference in each software in order to choose the most accurate of all.

The Digital Surface Model is the basis of the orthomosaic and so, is the fundamental key to achieve accurate results in geometry and quality of the final orthorectification. To accurately measure the differences in models, they were subtracted between each other and were computed zonal statistics over the whole area, and over some polygons representing areas with buildings, fields and others. Colormaps are presented, all with the same scale with red (minimum value to -0,5), next with yellow (-0,5 to 0), green (0 to 0,5) and finally blue (0,5 to maximum value).

Quality estimate is more prone to subjectivity, mainly with visualization aspects such as building edges and radiometric equalization. These features will be described from a user perspective, with visualization in detail of said aspects. Profiles from DEM of each software are represented with blue being PhotoScan, red is Pix4Dmapper and green being MicMac.

4.1. UTAD data

In the first area, RGB and NIR imagery were acquired, so it would be possible to compare data with different wavelengths. Some software could have some advantages or disadvantages dealing with this different kind of imagery and is important to identify that ability to further proceed the complete analysis in the software of this study.

Firstly, a relative review, with 10 comparison points with planimetric and altimetric data from each software. The NIR case is short on one comparison point because at time of flight, its view was obstructed, thus the analysis was made with the remaining 9 points. The results from each camera are displayed in Table 6.

Table 6 – Relative comparison values, for UTAD, between each software, for RGB and NGB imagery

Relative RGB (10 comparison points)									
Software	**PhotoScan-Pix4Dmapper**			**PhotoScan-MicMac**			**Pix4Dmapper-MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	0.036	0.058	**0.066**	0.020	0.043	**0.045**	-0.017	0.039	**0.041**
Y	0.026	0.043	**0.048**	0.030	0.045	**0.052**	0.004	0.029	**0.028**
XY (norm)	0.075	0.034	**0.081**	0.062	0.032	**0.069**	0.048	0.014	**0.050**
Z	0.250	0.383	**0.441**	0.240	0.380	**0.433**	-0.010	0.062	**0.060**
Relative NGB (9 comparison points)									
Software	**PhotoScan-Pix4Dmapper**			**PhotoScan-MicMac**			**Pix4Dmapper-MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.098	0.142	**0.166**	-0.029	0.159	**0.153**	0.069	0.129	**0.140**
Y	0.006	0.105	**0.100**	-0.035	0.070	**0.075**	-0.041	0.059	**0.069**
XY (norm)	0.169	0.099	**0.193**	0.151	0.083	**0.170**	0.135	0.083	**0.156**
Z	0.165	0.430	**0.438**	0.265	0.457	**0.506**	0.100	0.199	**0.213**

The planimetric differences for each solution are well within ground sampling distance (10cm) and translate into an accordance between all software, being more evident on the comparison Pix4Dmapper - MicMac. On the other side, the altitude is where the errors are naturally larger but in this case are larger than 20cm sampling distance for altitude, with the differences to PhotoScan being significantly bigger than the ones between Pix4Dmapper and MicMac. The differences in the NIR case are even more accentuated but with MicMac and Pix4Dmapper being the closest to each other.

Several reasons could point to this discrepancy like the presence of errors in the model produced by PhotoScan, or that Pix4D and MicMac produce similar results, therefor little changes between them. Some of the points chosen for this relative

comparison were near trees and buildings which lead to some noise being present in that area in the point dense cloud, ultimately resulting in faults on the final model. For these reasons, a more robust method of examination is needed, meaning the introduction of check points with ground truth in this analysis, calculating the displacement of the final products, in Table 7.

Table 7 –– Absolute comparison values, for UTAD, between each software, for RGB and NGB imagery

Absolute RGB (5 check points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.019	0.037	**0.038**	-0.012	0.031	**0.030**	-0.018	0.017	**0.023**
Y	-0.066	0.039	**0.074**	-0.061	0.020	**0.064**	-0.022	0.031	**0.035**
XY (norm)	0.079	0.031	**0.084**	0.068	0.019	**0.070**	0.036	0.024	**0.042**
Z	-0.135	0.046	**0.142**	0.014	0.076	**0.070**	-0.016	0.067	**0.062**
Absolute NGB (5 check points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.060	0.023	**0.064**	-0.107	0.084	**0.131**	-0.004	0.012	**0.012**
Y	-0.057	0.071	**0.086**	-0.016	0.036	**0.036**	-0.045	0.060	**0.070**
XY (norm)	0.095	0.054	**0.107**	0.126	0.057	**0.136**	0.066	0.027	**0.071**
Z	-0.135	0.078	**0.152**	-0.104	0.048	**0.112**	-0.046	0.105	**0.105**

Initially, the check points were only 5, meaning that there is little statistical significance, but still a good precision measure. The distribution of those points was also a bit biased because in this mixed rural area, it was difficult to find well defined points dispersed throughout the whole scene and visible. Later it was added another check point with known coordinates from another surveying, located in the south region (sports field), a zone lacking in control and check points to evaluate the possible precision lowering and its statistics is present in Table 8.

Table 8 – Absolute comparison values, for UTAD, between each software, for RGB and NGB imagery, with added point

Absolute RGB (6 check points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.015	0.034	**0.035**	-0.007	0.030	**0.028**	-0.014	0.018	**0.022**
Y	-0.060	0.038	**0.069**	-0.047	0.040	**0.059**	-0.010	0.040	**0.038**
XY (norm)	0.071	0.034	**0.078**	0.062	0.023	**0.066**	0.039	0.023	**0.044**
Z	-0.153	0.060	**0.163**	0.060	0.131	**0.134**	0.027	0.121	**0.114**
Absolute NGB (6 check points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.066	0.025	**0.070**	-0.124	0.085	**0.146**	0.004	0.021	**0.020**
Y	-0.060	0.064	**0.084**	-0.022	0.036	**0.040**	-0.056	0.060	**0.078**
XY (norm)	0.099	0.049	**0.109**	0.140	0.062	**0.152**	0.075	0.032	**0.081**
Z	-0.143	0.073	**0.157**	-0.052	0.135	**0.133**	0.047	0.245	**0.228**

Analyzing the results from both RGB and NIR from Table 7, MicMac stand outs as the most accurate in geometry, both in planimetry and altitude. All software shows below GSD differences, averaging 7 to 8 centimeters, while MicMac pushes down to 4 centimeters in XY. In all software the accuracy is similar and bellow GSD in both planimetry and altimetry. In the Infrared imagery, the commercial solutions seem to decrease their performance, especially Pix4Dmapper, being slightly above ground sampling distance for this area. In altitude there is a clear deterioration of precision in Pix4Dmapper and MicMac, elevating the difference up to 10-11 centimeters, while PhotoScan keeps almost the same result, not being so affected by the change in the wavelength.

From the Table 8, with the added check point, results were clearly affected in altitude, especially MicMac and Pix4Dmapper in both cases, pointing to a bad terrain altitude modeling in that specific area, consequence of biased GCP location. PhotoScan didn't suffer so much with this effect with minimal changes, up to 2 cm. This strange behavior needed to be clarified and, with later DEM analysis, was found that there was a clear deviation of terrain modeling in both Pix4Dmapper and MicMac, against PhotoScan. Therefore, 39 check points were collected, together with more GCP, now totaling 15 across the whole area, and are all represented in Figure 36 with the same previous color reference.

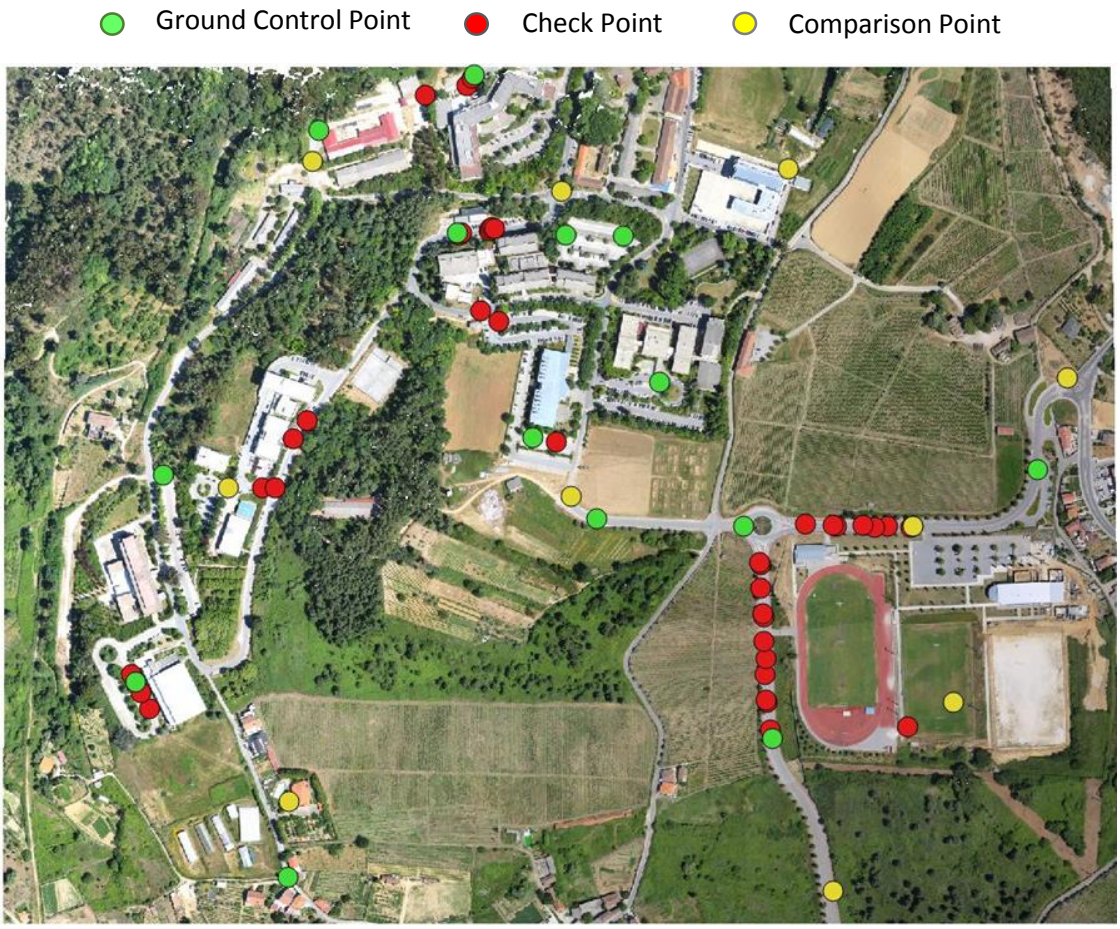


Figure 36 – Representation of the all the points used for new analysis in UTAD

Table 9 – Absolute comparison values, for UTAD, between each software, for RGB and NGB imagery with 39 check points

Absolute RGB (39 Check Points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.030	0.060	**0.066**	0.000	0.044	**0.045**	0.017	0.044	**0.047**
Y	0.022	0.053	**0.062**	-0.020	0.050	**0.055**	0.016	0.048	**0.051**
XY (norm)	0.078	0.043	**0.091**	0.062	0.032	**0.071**	0.061	0.032	**0.070**
Z	-0.032	0.111	**0.122**	-0.023	0.099	**0.103**	0.004	0.078	**0.079**
Absolute NGB (39 Check Points)									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.055	0.046	**0.073**	-0.070	0.060	**0.093**	0.024	0.048	**0.054**
Y	0.017	0.045	**0.049**	-0.029	0.059	**0.066**	0.014	0.063	**0.065**
XY (norm)	0.077	0.039	**0.088**	0.100	0.052	**0.114**	0.071	0.045	**0.085**
Z	-0.120	0.106	**0.162**	-0.143	0.116	**0.187**	0.133	0.174	**0.222**

Now, with more statistical significance, MicMac is again the most accurate in geometry, both planimetric and altimetric in RGB, followed closely by Pix4Dmapper and all software show bellow GSD accuracy. In infrared imagery, the result was the same as the previous processing, with deterioration of altimetric precision, more evident in Pix4D and MicMac. The last one still stands out as the most accurate in planimetric geometry in both kinds of imagery. The difference in near infrared could be explained by the added vegetation introduced by this wavelength, combined with the removal of those elements, can create some noise in those areas. PhotoScan doesn't have the best results but remains almost unchanged in planimetry, and with little difference in altimetry, when comparing RGB to NGB imagery.

In general, the different wavelength leads to loss of accuracy across all software but MicMac and PhotoScan seem to be the best solutions in planimetry and altimetry, respectively, when dealing with this kind of imagery.

The data was also processed without GCP and the differences between GCP ground truth and their respective location in each product were calculated, translating in the Table 10.

Table 10 – Absolute comparison values, for UTAD, between each software, without GCP

Without GCP RGB									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.354	1.737	**1.647**	-0.529	0.037	**0.530**	-0.591	0.011	**0.591**
Y	-0.602	1.043	**1.138**	-2.106	0.066	**2.107**	-2.129	0.026	**2.129**
XY	1.711	1.122	**2.002**	2.171	0.065	**2.172**	2.209	0.025	**2.209**
Z	-7.019	1.006	**7.080**	-3.324	0.106	**3.326**	-3.233	0.120	**3.235**
Without GCP NGB									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	0.335	8.923	**8.268**	-0.267	0.042	**0.269**	-0.384	0.158	**0.411**
Y	6.390	5.877	**8.393**	-1.106	0.069	**1.108**	-1.083	0.088	**1.086**
XY	10.698	5.330	**11.781**	1.138	0.075	**1.141**	1.160	0.067	**1.162**
Z	-20.112	4.805	**20.599**	-2.553	0.390	**2.578**	-2.646	0.404	**2.672**

As expected, the results range several meters, with the georeferencing from RPAS GNSS module, equipped with standard code single frequency receiver. With RGB imagery, PhotoScan had slightly the best behavior without GCP in planimetry, while the

other two solutions had better results in NIR. This goes against previous calculations where Pix4Dmapper displayed a worse performance than the others, but this is verified only with GCP, because in this case, its performance is similar to MicMac's. On the other hand, PhotoScan processing in NIR was poor, with bad camera calibration calculation, resulting in a nonlinear distortion in the final model, thus producing the huge differences present in the table. To investigate this occurrence, other flights in archive were selected, one from the same area but from an earlier date, another from same area but different flight height and another from a vineyard farm near Pinhão. They were rapidly processed in PhotoScan to eliminate any doubts about NIR processing. In every test there was a presence of a bowl effect like the Figure 37, meaning that this software from Agisoft has some kind of difficulty dealing with near infrared imagery, leading to bad camera calibration and nonlinear distortions, when not using GCP. A solution for this would be saving camera calibration from another processing with the same camera and with GCP. Even with this solution there could exist calibration error due to the unknown effect that the NIR filter can have inside the optical system.

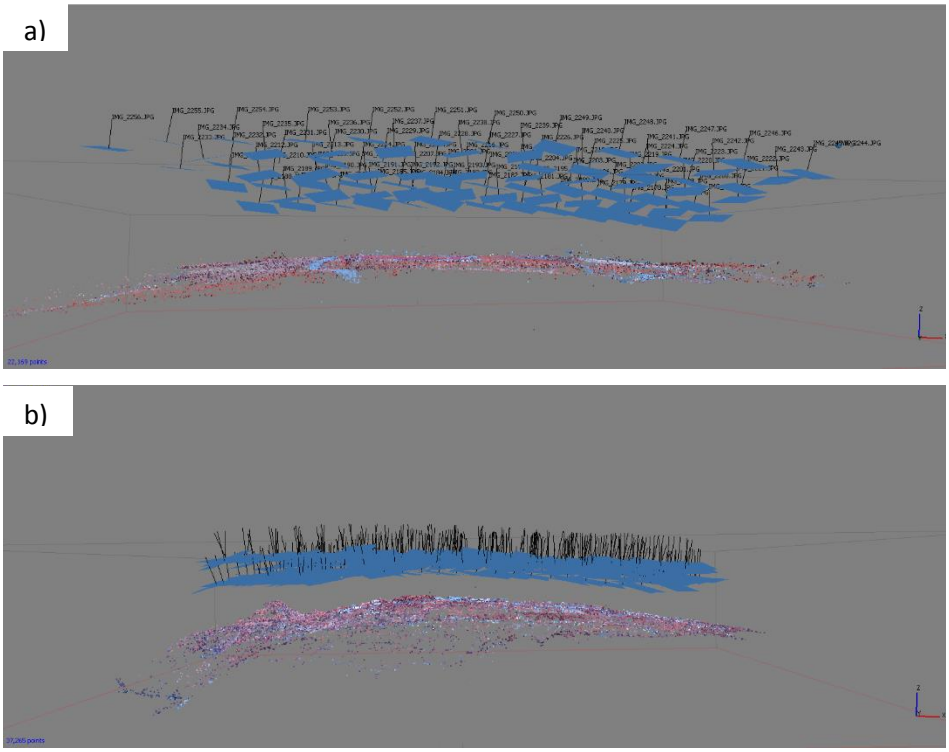


Figure 37 – Image a) from UTAD and b) from vineyard in Pinhão, representing bowl effect on NIR data processed with PhotoScan

Another important thing to notice is the extreme similarity in results from Pix4Dmapper and Micmac. More noticeable in this case, the precisions achieved are very close on both cases and confirmed by the difference calculated earlier with GCP.

PhotoScan output precisions are most of the times well-spaced from the other software, while Pix4Dmapper and MicMac are very close. This could hint that some steps of processing are using the same tools in both solutions.

4.1.1. DEM analysis

The difference between DEM generated by each solution was calculated and is presented on the following figures: Figure 38, Figure 39, Figure 40, Figure 41, Figure 42, Figure 43, Figure 44, Figure 45, Figure 46, Figure 47, Figure 48 and Figure 49, by a histogram and colormap of every situation.

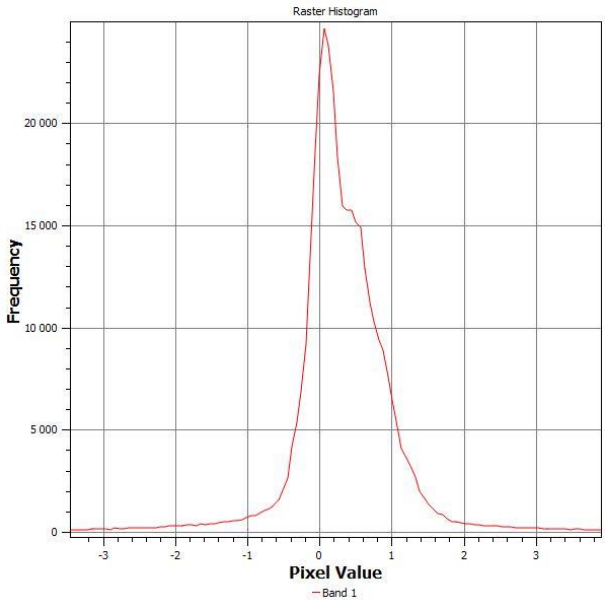


Figure 38 – DEM difference histogram from PhotoScan-Pix4Dmapper RGB

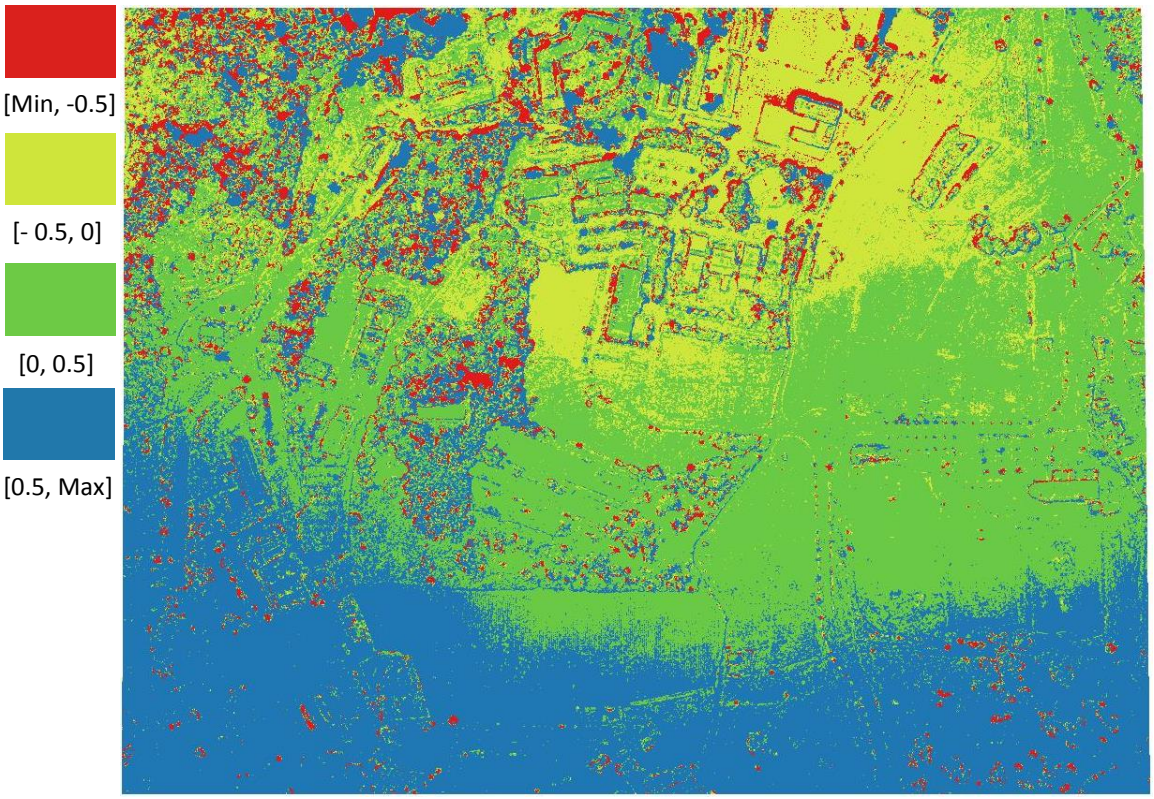


Figure 39 – Colormap of DEM differences, from PhotoScan-Pix4Dmapper RGB

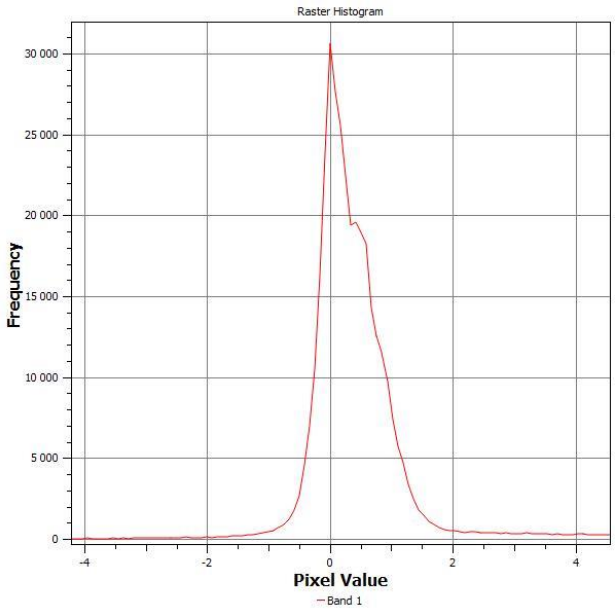


Figure 40 – DEM difference histogram from PhotoScan-MicMac RGB

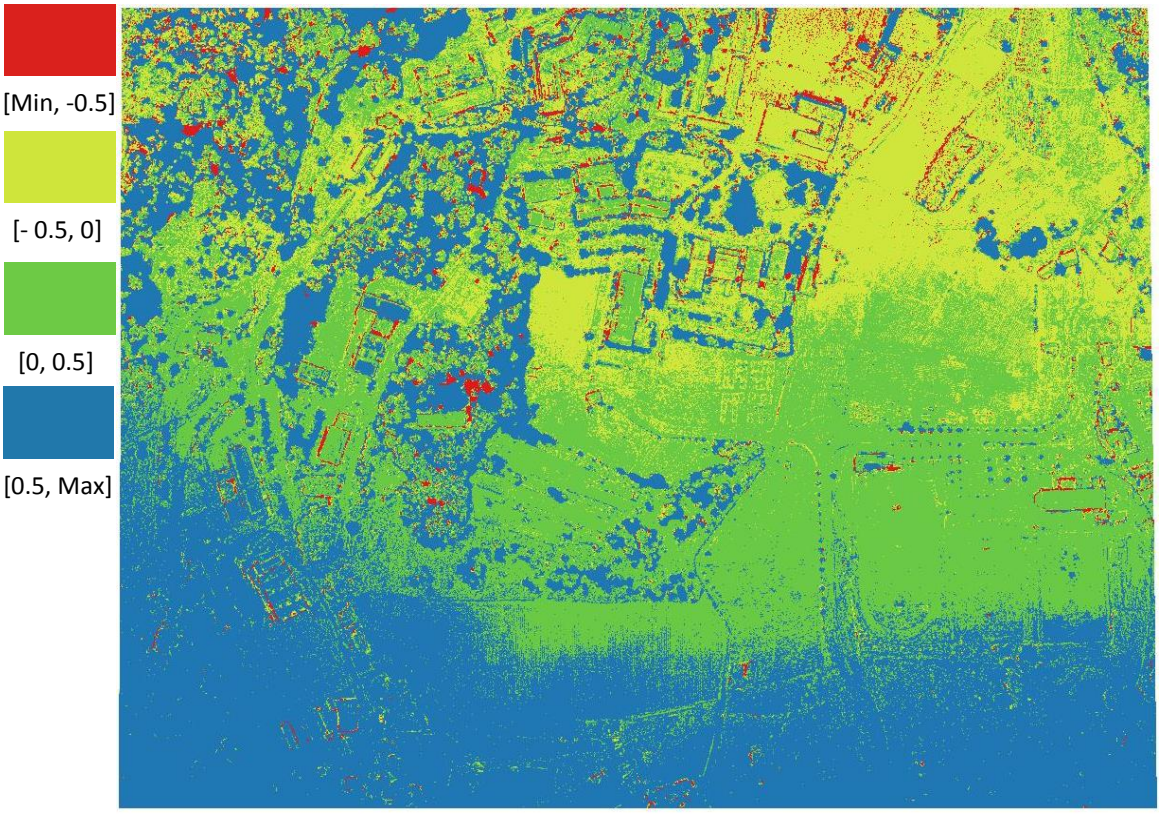


Figure 41 – Colormap of DEM differences, from PhotoScan-MicMac RGB

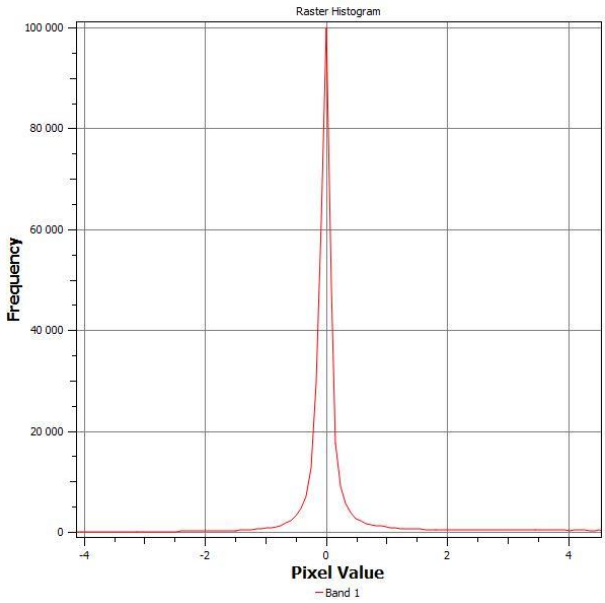


Figure 42 – DEM difference histogram from Pix4Dmapper-MicMac RGB

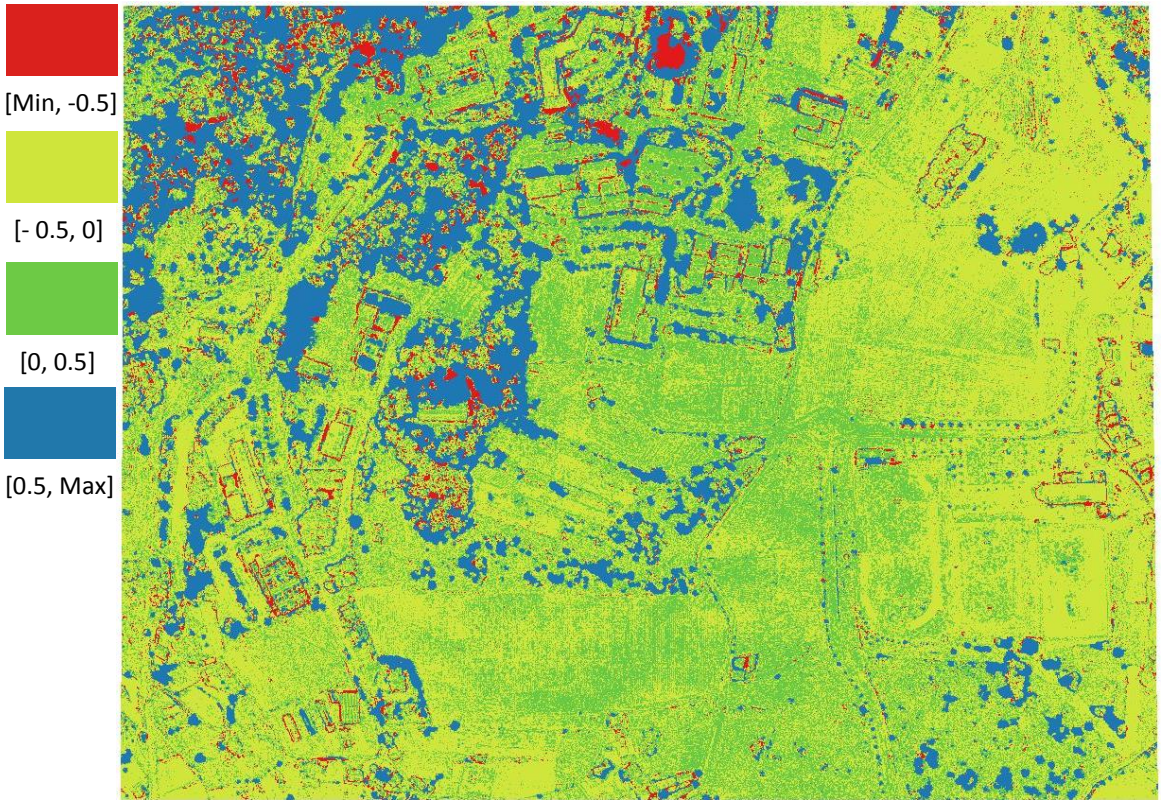


Figure 43 – Colormap of DEM differences, from Pix4Dmapper-MicMac RGB

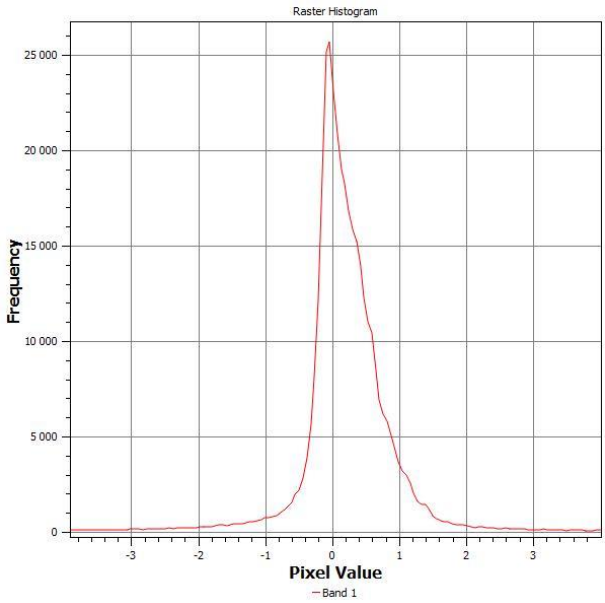


Figure 44 – DEM difference histogram from PhotoScan-Pix4Dmapper NGB

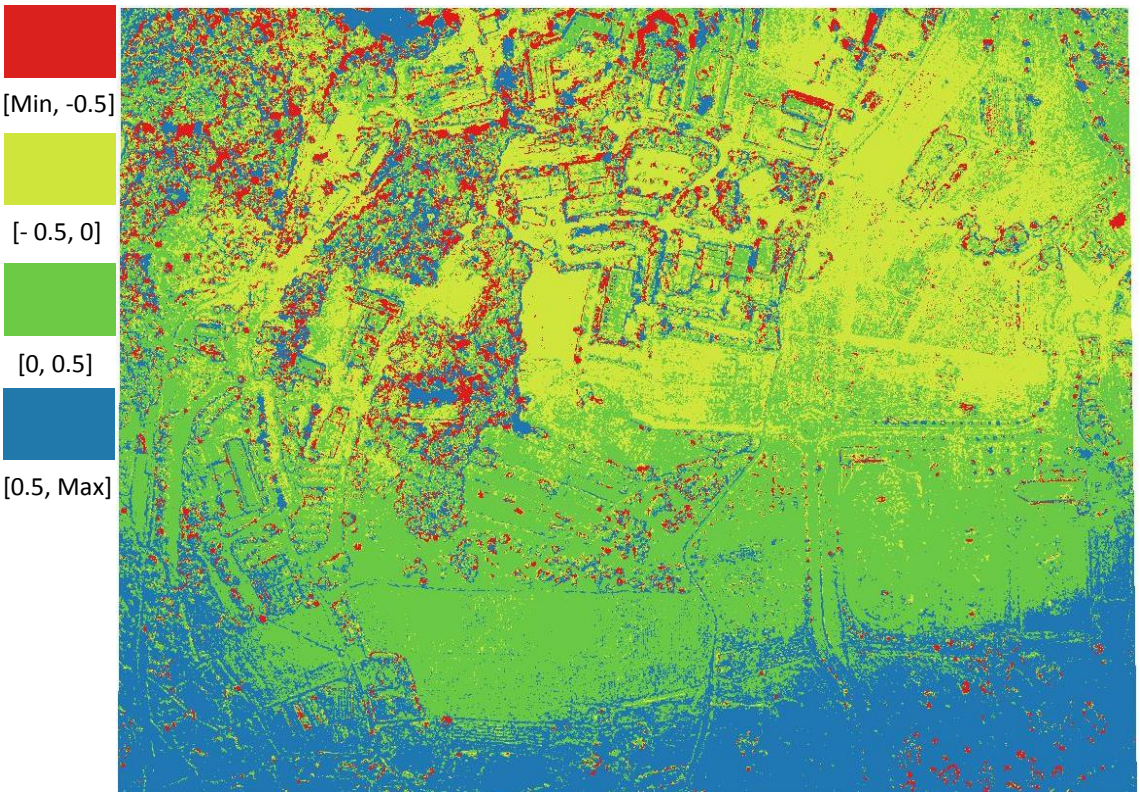


Figure 45 – Colormap of DEM differences, from PhotoScan-Pix4Dmapper NGB

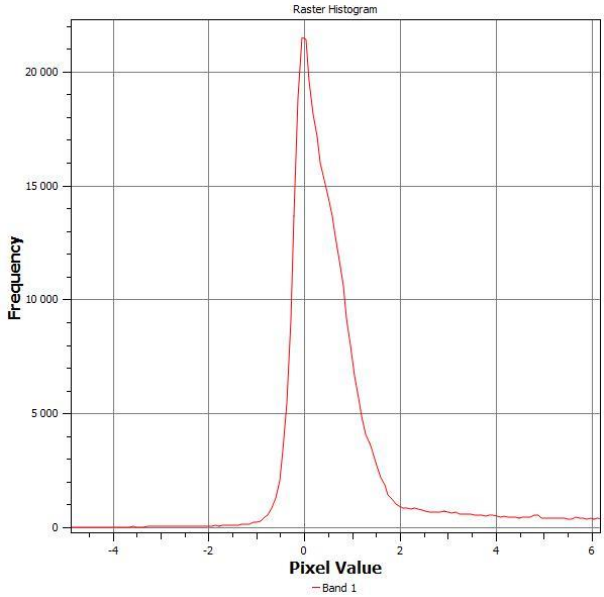


Figure 46 – DEM difference histogram from PhotoScan-MicMac NGB

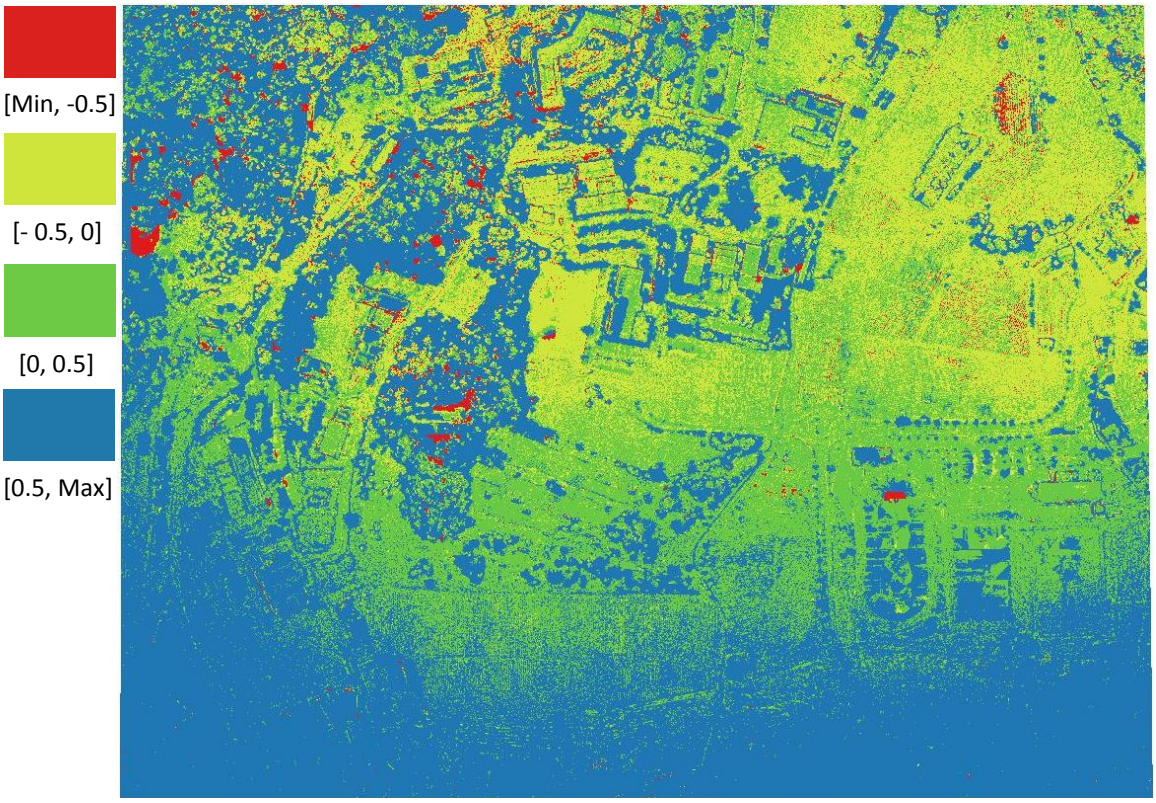


Figure 47 – Colormap of DEM differences, from PhotoScan-MicMac NGB

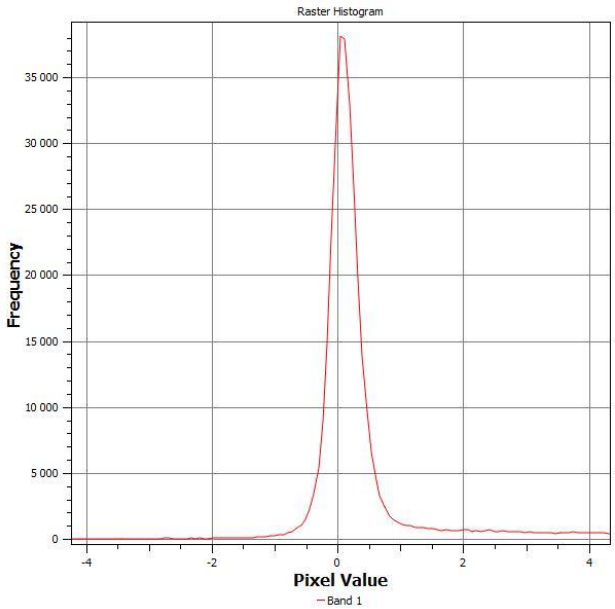


Figure 48 – DEM difference histogram from Pix4Dmapper-MicMac NGB

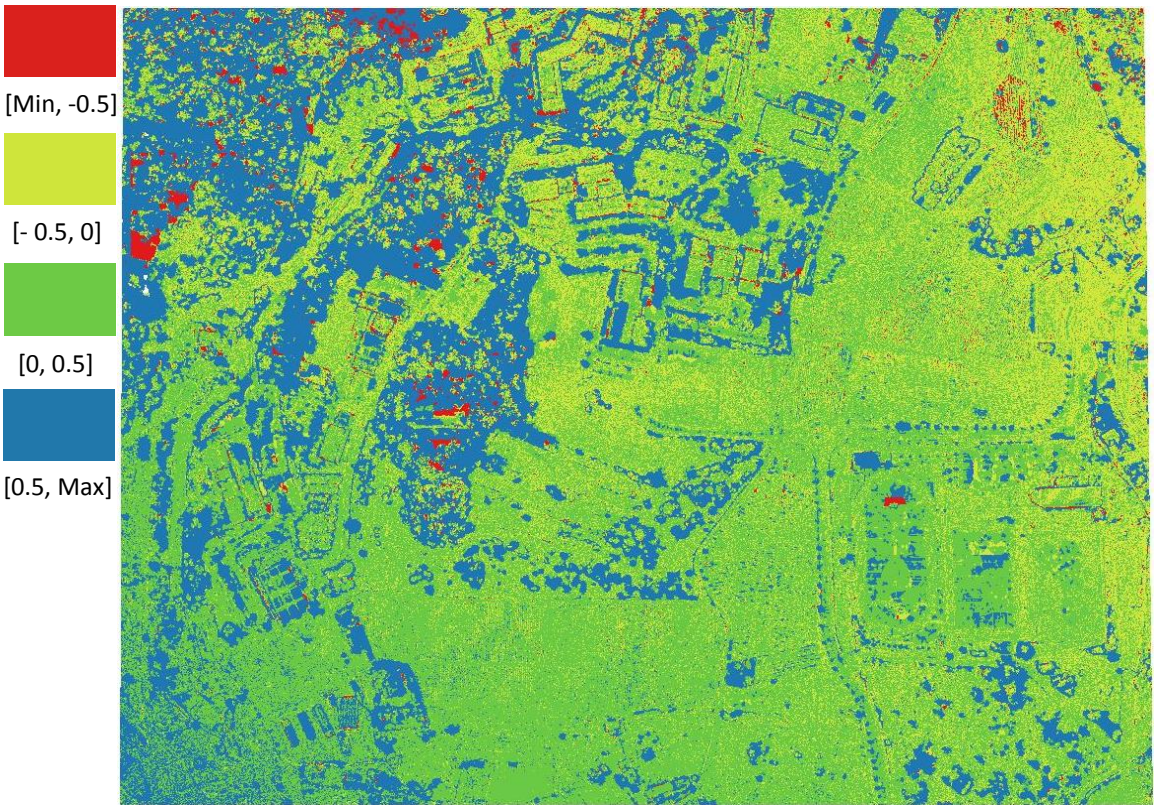


Figure 49 – Colormap of DEM differences, from Pix4Dmapper-MicMac NGB

The major noticeable variation comes from PhotoScan against the other software, where the south area produces the biggest differences. This is in agreement with the previous analysis with check points which indicated that PhotoScan had a better

reconstruction in that southern zone, despite not being covered with GCP. This fact also explains the positive tendency found in histograms.

The reasonable explanation for this event is the flight altitude during the surveying of that zone being higher. Both software, Pix4Dmapper and MicMac, used the metadata stored in the images for calculating approximate heights when lacking GCP. As Agisoft claims, PhotoScan is a software written from scratch for photogrammetry and it could have some other processing methods that allowed it to better reconstruct the whole scene, even with few GCP for structure corrections. On the other side, Pix4Dmapper and MicMac hint again for some common processing tools or methods.

The same analysis was done over the newly generated DEM with the added GCP, presented in Figure 50, Figure 51, Figure 52, Figure 53, Figure 54, Figure 55, Figure 56, Figure 57, Figure 58, Figure 59, Figure 60 and Figure 61.

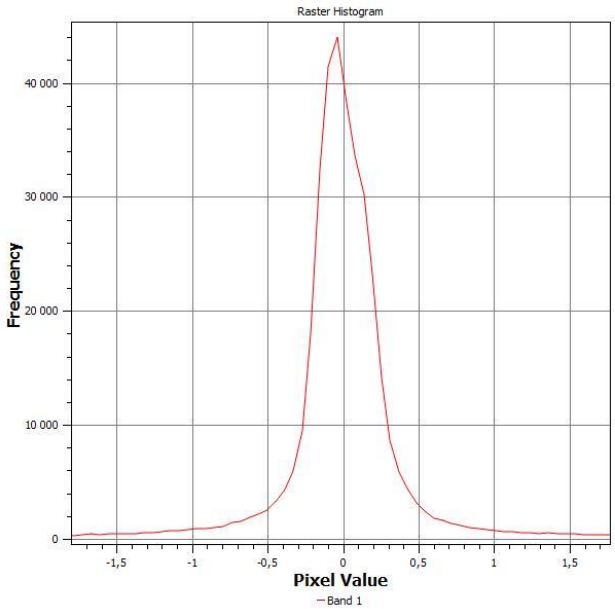


Figure 50 – DEM difference histogram from new PhotoScan-Pix4Dmapper RGB

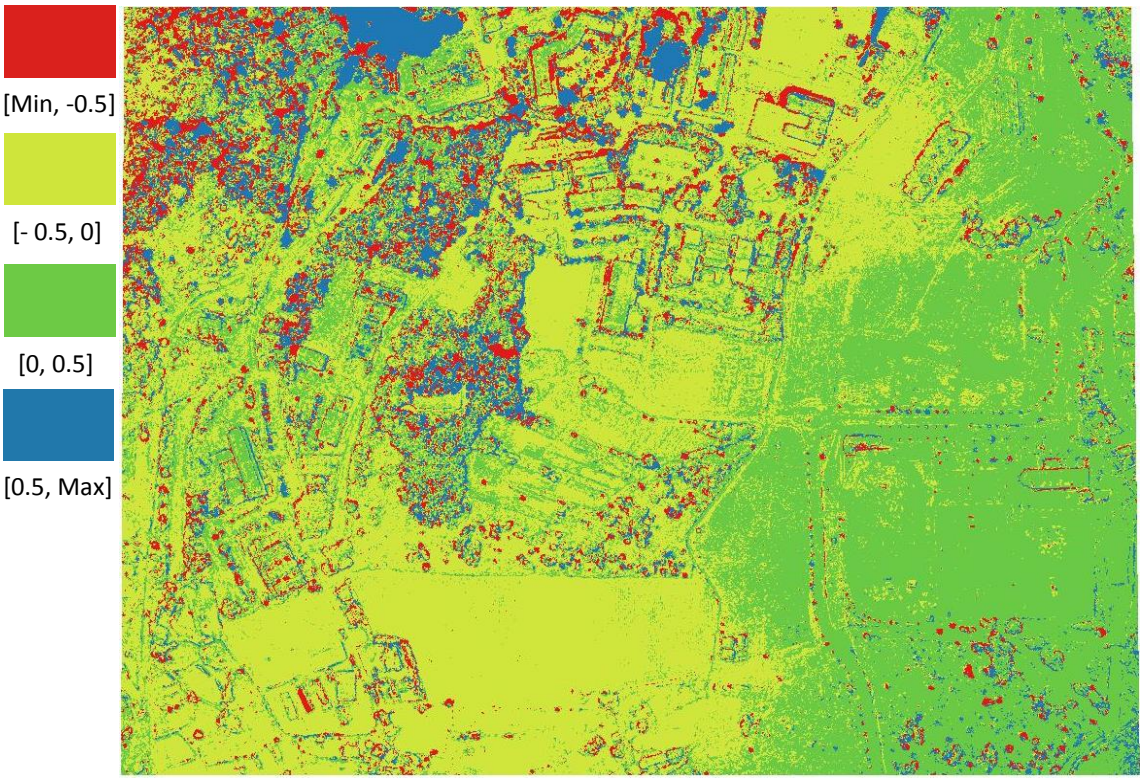


Figure 51 – Colormap of DEM differences, from new PhotoScan-Pix4Dmapper RGB

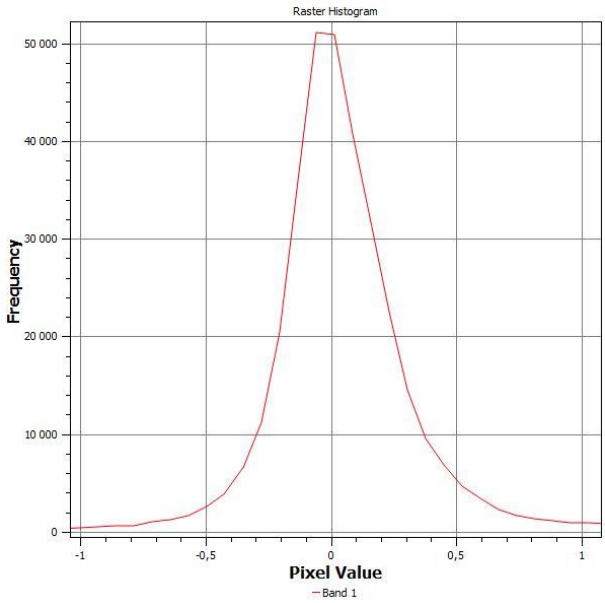


Figure 52 – DEM difference histogram from new PhotoScan-MicMac RGB

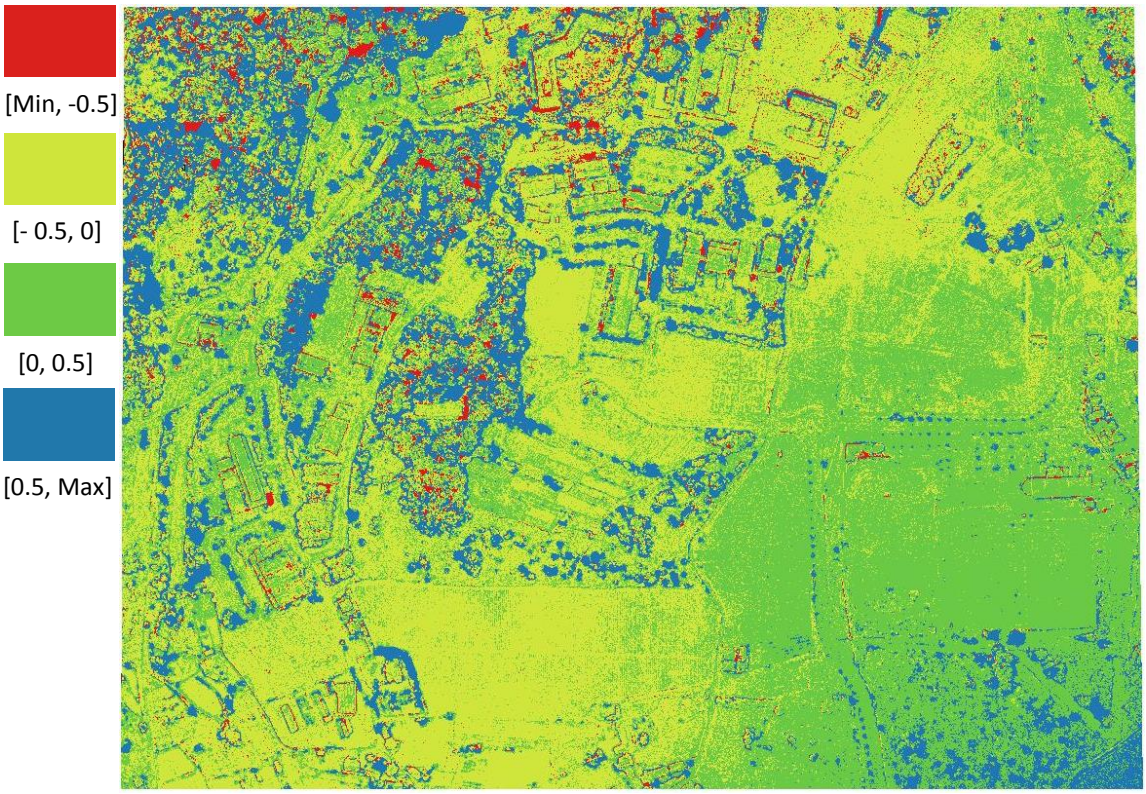


Figure 53 – Colormap of DEM differences, from new PhotoScan-MicMac RGB

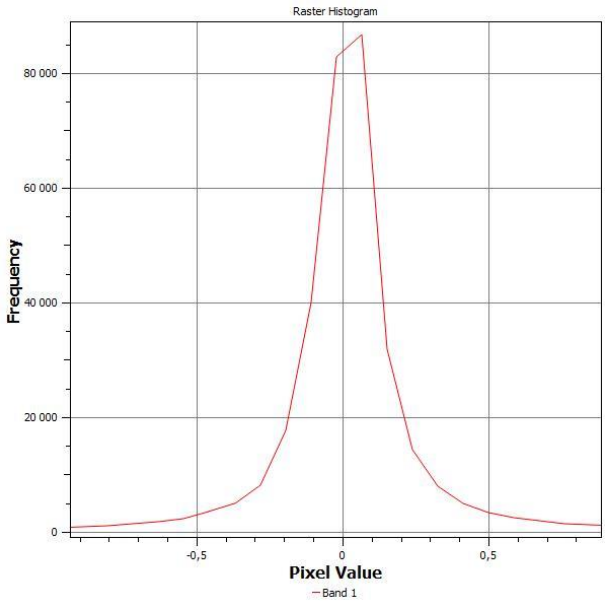


Figure 54 – DEM difference histogram from new Pix4Dmapper-MicMac RGB

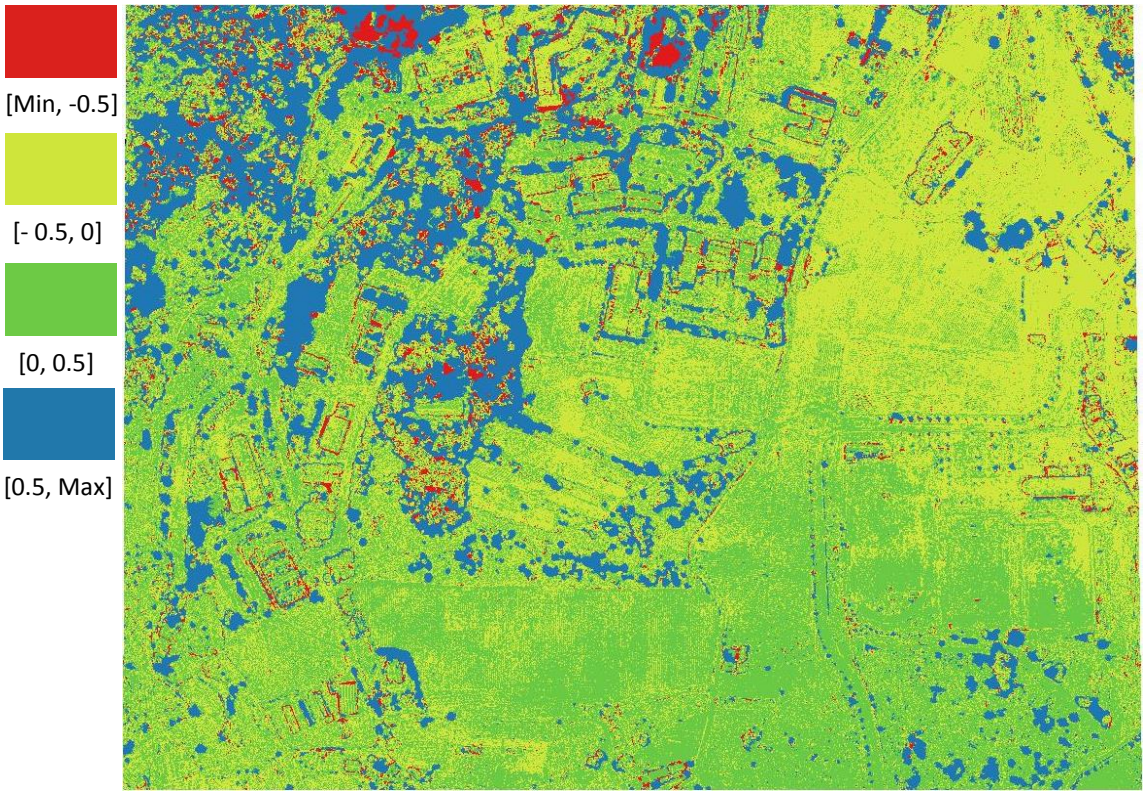


Figure 55 – Colormap of DEM differences, from new Pix4Dmapper-MicMac RGB

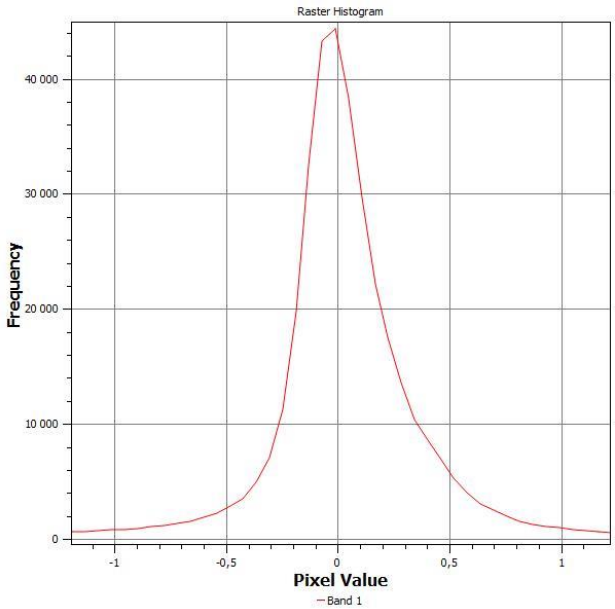


Figure 56 – DEM difference histogram from new PhotoScan-Pix4Dmapper NGB

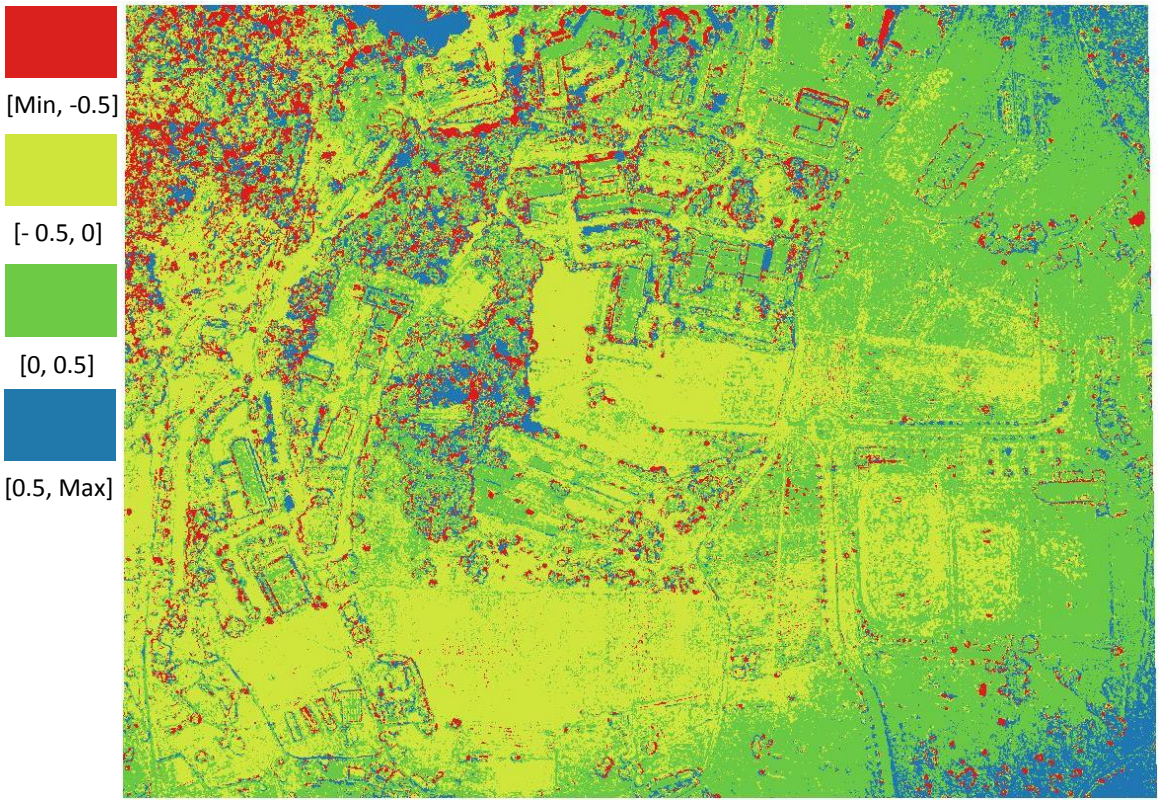


Figure 57 – Colormap of DEM differences, from new PhotoScan-Pix4Dmapper NGB

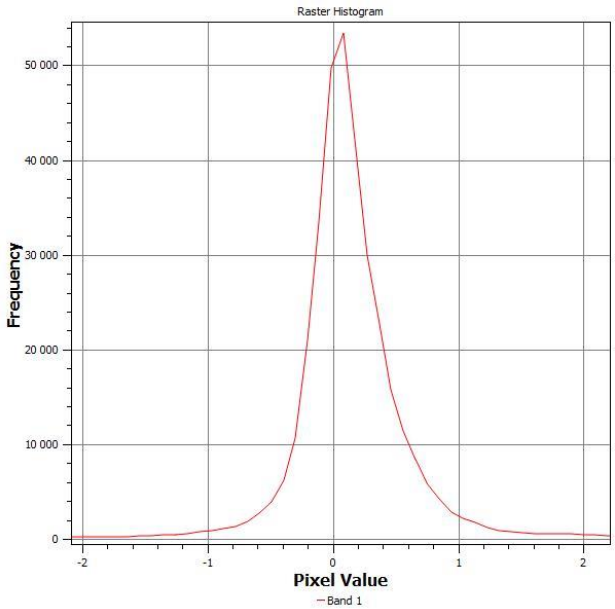


Figure 58 – DEM difference histogram from new PhotoScan-MicMac NGB

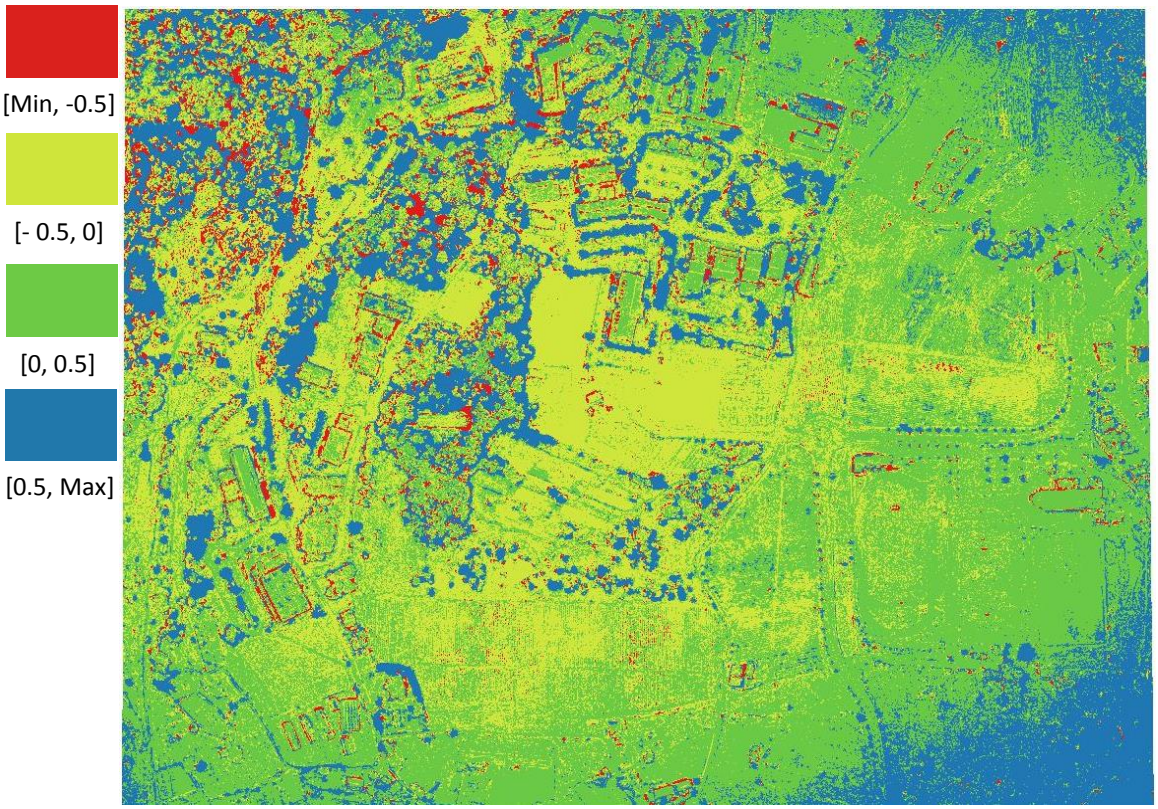


Figure 59 – Colormap of DEM differences, from new PhotoScan-MicMac NGB

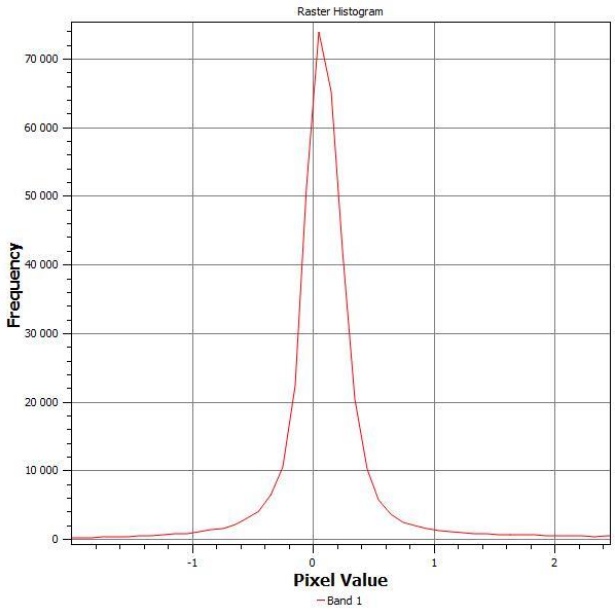


Figure 60 – DEM difference histogram from new Pix4Dmapper-MicMac NGB

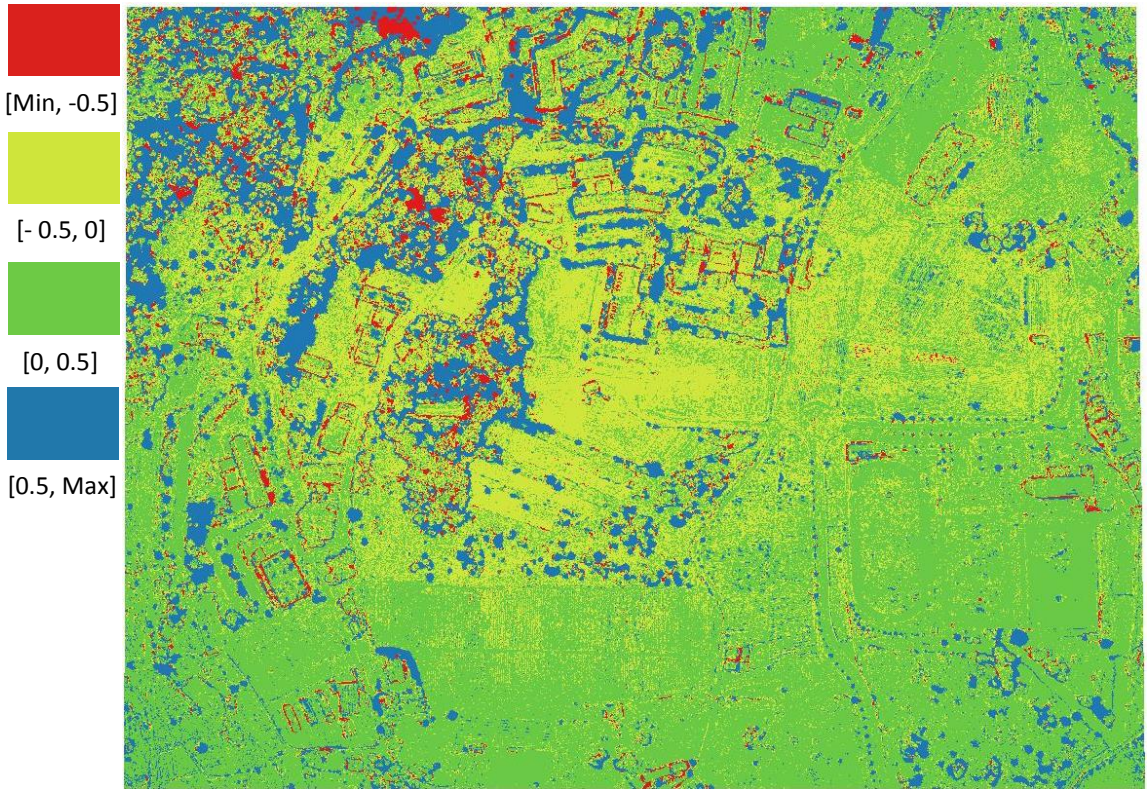


Figure 61 – Colormap of DEM differences, from new Pix4Dmapper-MicMac NGB

The major changes in RGB are noticeable in the right side where again there are few GCP. While in NGB there are some differences in the edges from PhotoScan to the

other software. This is a direct result from the processing difficulties that PhotoScan suffers with this kind of imagery.

Table 11 represents the statistics over the DEM difference, validating the positive tendency in histograms, by their mean values.

Table 11 – DEM difference statistics of UTAD

RGB	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
PhotoScan-Pix4Dmapper	0,111	-0,010	1,936	-34,450	32,753
PhotoScan-MicMac	1,063	0,035	3,975	-26,937	50,665
Pix4Dmapper-MicMac	0,952	0,035	3,842	-29,983	51,593
NGB	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
PhotoScan-Pix4Dmapper	0,085	0,009	1,660	-29,382	32,528
PhotoScan-MicMac	1,101	0,105	4,098	-26,582	71,547
Pix4Dmapper-MicMac	1,016	0,086	3,981	-28,717	72,901

The first DEM difference with a mean of around 0,1 meters translates into a very similar modelling from the commercial applications. On the other hand, MicMac has even more positive influence due to the trees cut from its model, explaining the mean highest value. Against Pix4Dmapper, the major differences are again the trees and some building edges. In NIR imagery the different building modelling and vegetation difference is even more accentuated in MicMac, producing results with more vegetation and some building errors.

Histograms and colormaps were also computed to better display the difference in elevation between RGB and NGB imagery, displayed in Figure 62, Figure 63, Figure 64, Figure 65, Figure 66 and Figure 67.

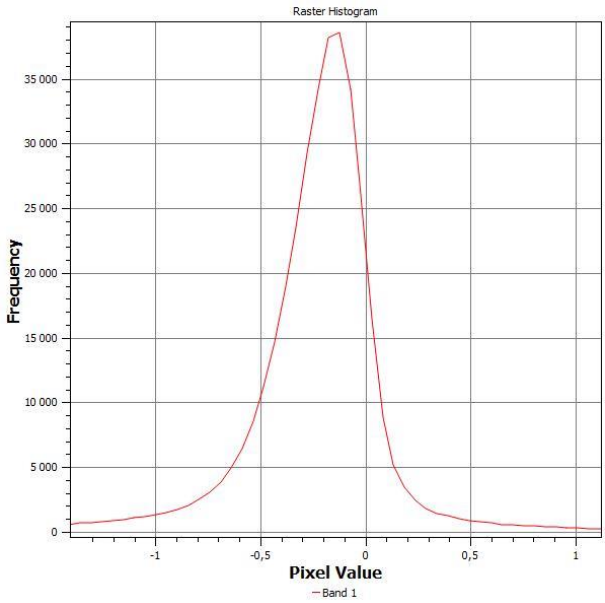


Figure 62 – DEM difference histogram from new PhotoScan RGB-NGB

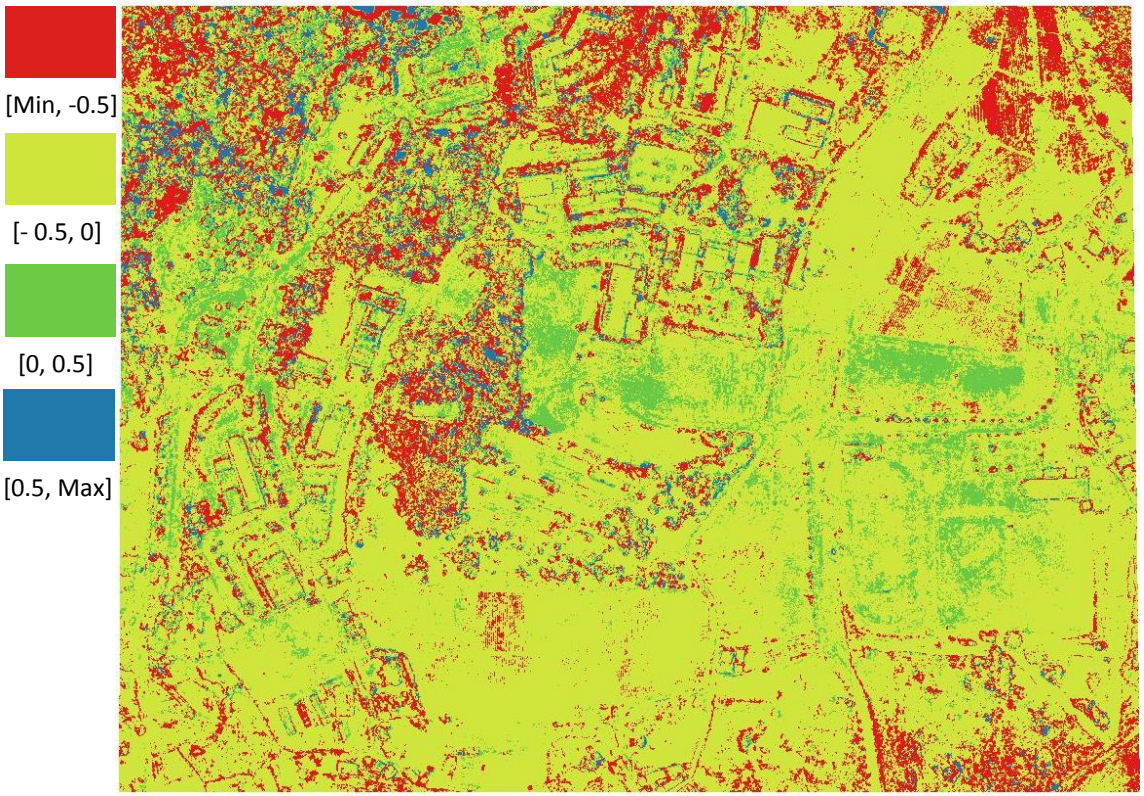


Figure 63 – Colormap of DEM differences, from new PhotoScan RGB-NGB

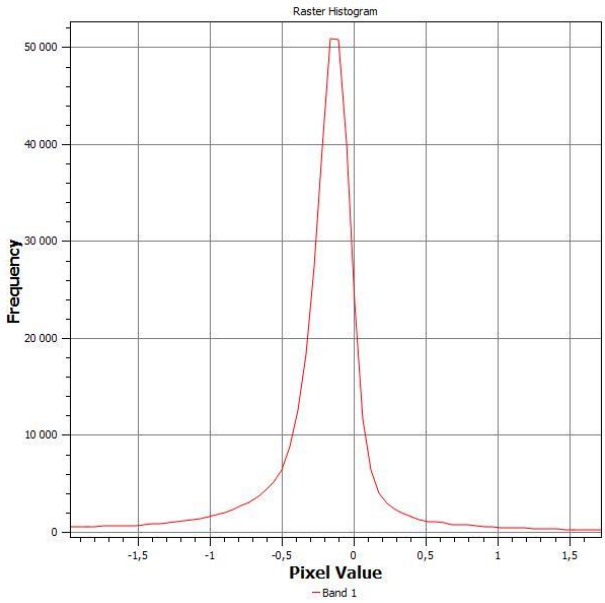


Figure 64 – DEM difference histogram from new Pix4Dmapper RGB-NGB

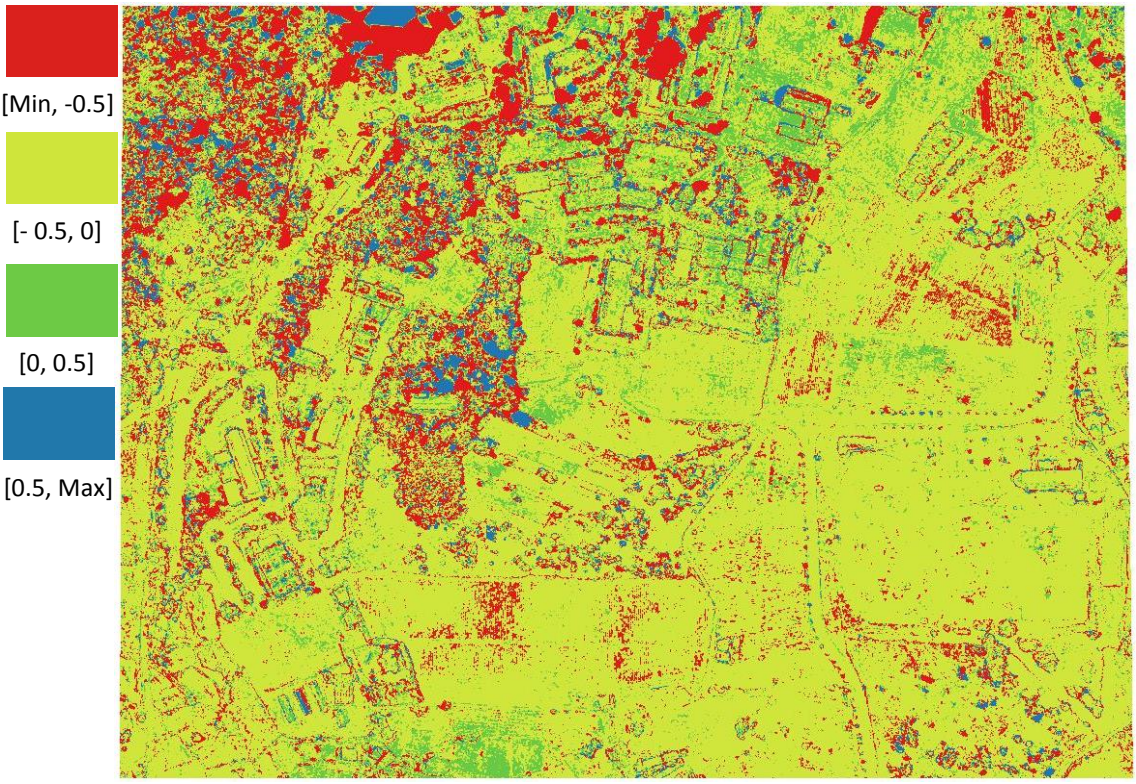


Figure 65 – Colormap of DEM differences, from new Pix4Dmapper RGB-NGB

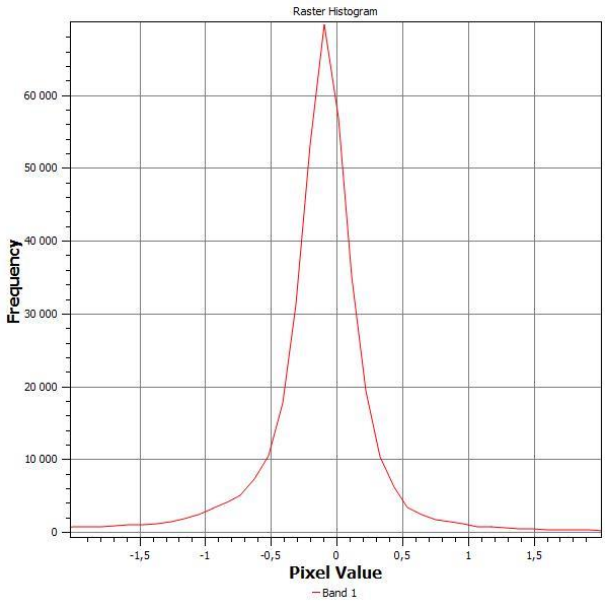


Figure 66 – DEM difference histogram from new MicMac RGB-NGB

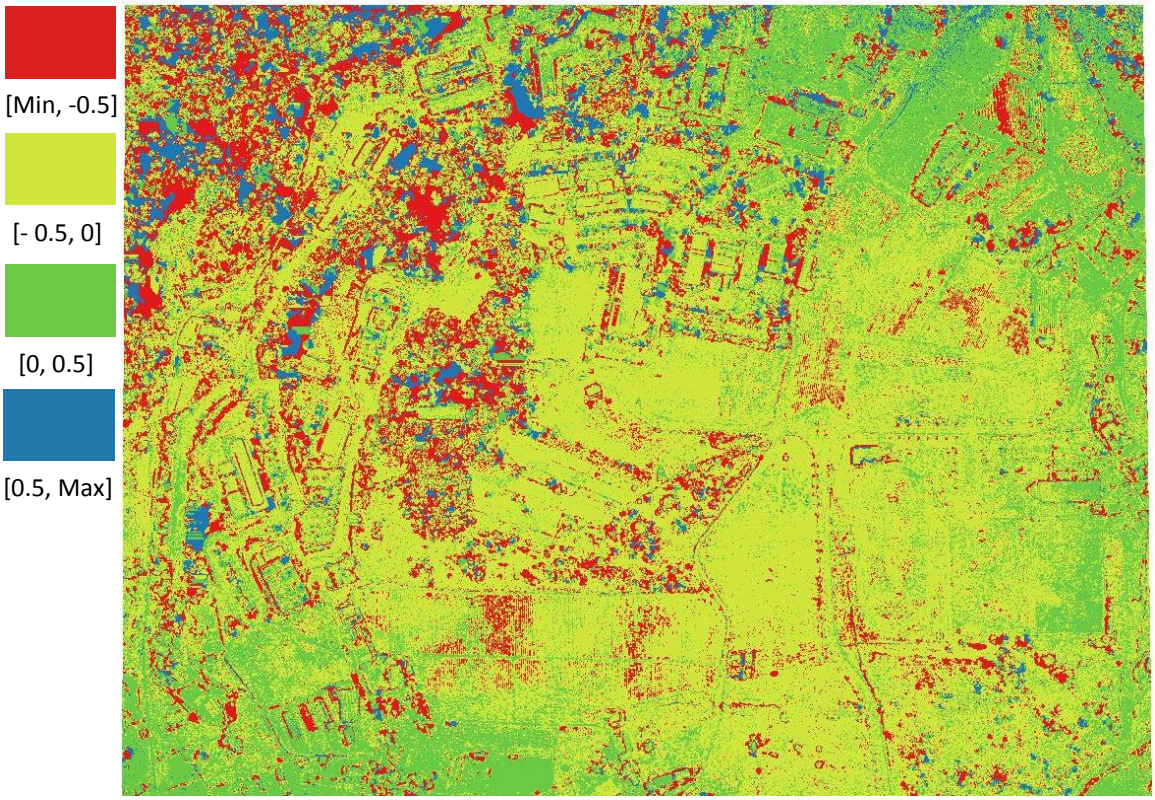


Figure 67 – Colormap of DEM differences, from new MicMac RGB-NGB

Analyzing the histograms, they all have a negative tendency explained by the presence of more vegetation in this kind of spectrum, also visible on the colormaps,

where the biggest differences are located specifically in vegetated zones and some building edges.

Smaller zones for statistic computing were created in locations across the entire area, displayed in Figure 68 by the red polygons.

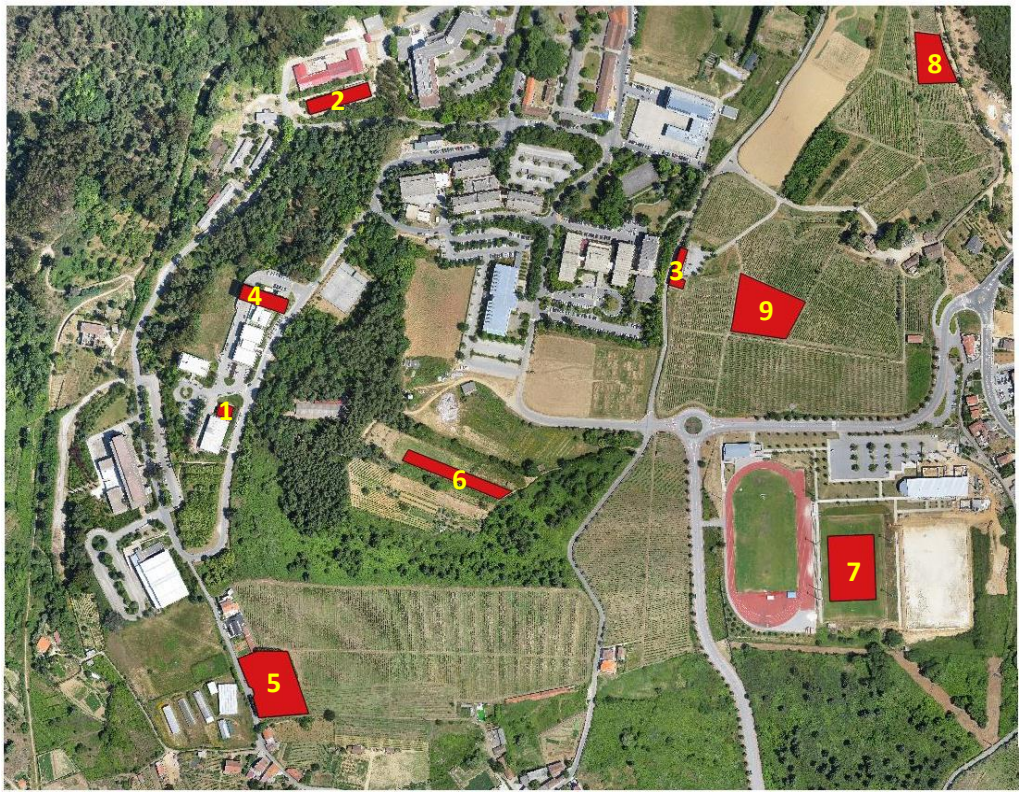


Figure 68 – Location of the chosen areas for detailed statistics, on UTAD

Table 12 – Relative statistics for the chosen areas, on RGB imagery, of UTAD

RGB					
Software	**PhotoScan-Pix4Dmapper**				
Polygon ID	**Mean (m)**	**Median (m)**	**Stand. Dev. (m)**	**Min (m)**	**Max (m)**
1	-0,160	-0,061	0,372	-1,837	1,461
2	-0,002	-0,026	0,238	-1,280	3,203
3	0,022	-0,011	0,447	-3,959	7,048
4	0,105	0,103	1,668	-14,371	17,499
5	-0,067	-0,150	1,205	-11,980	11,818
6	0,015	-0,010	0,098	-0,926	1,181
7	0,149	0,155	0,089	-1,622	0,772
8	0,158	0,164	0,103	-0,424	1,545
9	0,051	0,050	0,063	-0,788	0,406

Software	PhotoScan-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,022	-0,032	0,209	-3,108	1,521
2	-0,065	-0,056	0,241	-2,954	3,058
3	0,117	-0,025	0,861	-3,109	7,894
4	-0,174	0,017	1,204	-17,317	13,331
5	1,568	0,060	3,232	-6,923	14,043
6	0,023	-0,017	0,141	-0,731	1,422
7	0,205	0,206	0,093	-1,631	1,778
8	0,068	0,070	0,156	-0,868	1,922
9	0,024	0,021	0,082	-0,598	0,537
Software	Pix4Dmapper-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	0,138	0,023	0,390	-2,792	2,386
2	-0,063	-0,020	0,293	-3,793	2,362
3	0,095	0,002	0,787	-5,985	8,001
4	-0,280	-0,073	1,387	-18,175	13,233
5	1,635	0,141	3,294	-7,484	14,196
6	0,008	-0,007	0,107	-1,074	1,718
7	0,056	0,050	0,119	-0,810	2,196
8	-0,090	-0,093	0,148	-1,215	0,717
9	-0,028	-0,032	0,089	-0,689	1,146

Table 13 – Statistics for the chosen areas, on NGB imagery, of UTAD

NIR					
Software	PhotoScan-Pix4Dmapper				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,196	-0,106	0,340	-1,756	0,918
2	-0,125	-0,137	0,258	-3,373	2,829
3	0,127	0,088	0,657	-4,531	8,290
4	0,268	0,191	1,340	-4,491	20,304
5	0,006	-0,054	1,021	-10,595	12,679
6	0,024	-0,009	0,198	-2,000	1,460
7	-0,048	-0,033	0,155	-2,216	0,837
8	0,397	0,391	0,161	-0,300	3,094
9	0,077	0,077	0,152	-0,843	0,822

Software	PhotoScan-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,201	-0,139	0,320	-2,096	0,660
2	-0,124	-0,135	0,278	-4,129	2,530
3	0,007	0,043	0,672	-4,799	7,920
4	0,299	0,171	1,165	-5,893	20,507
5	1,543	0,177	3,371	-6,511	14,170
6	-0,034	-0,064	0,145	-0,725	1,753
7	0,122	0,133	0,163	-2,047	0,921
8	0,577	0,565	0,215	-0,984	4,063
9	0,104	0,078	0,204	-0,752	1,185
Software	Pix4Dmapper-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,005	-0,041	0,348	-1,694	1,706
2	0,000	-0,001	0,309	-5,237	1,991
3	-0,120	-0,066	0,589	-7,986	7,872
4	0,031	-0,021	1,622	-20,153	15,642
5	1,537	0,194	3,407	-7,148	14,454
6	-0,058	-0,065	0,162	-1,278	2,082
7	0,170	0,164	0,179	-1,849	2,356
8	0,181	0,178	0,201	-2,018	2,244
9	0,027	-0,006	0,204	-0,969	1,503

Table 14 – Statistics of the differences between RGB and NGB imagery of UTAD, for each software

RGB-NIR					
Software	PhotoScan				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,012	-0,046	0,206	-1,799	0,989
2	-0,017	-0,014	0,156	-1,854	2,211
3	-0,155	-0,195	0,356	-1,870	4,103
4	-0,500	-0,241	1,170	-15,019	5,275
5	-0,451	-0,278	1,072	-11,618	10,068
6	-0,095	-0,097	0,151	-1,391	1,244
7	-0,040	-0,029	0,091	-0,650	1,161
8	-0,560	-0,571	0,210	-2,756	0,645
9	-0,271	-0,240	0,184	-1,026	0,119

Software	Pix4Dmapper				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,048	-0,080	0,344	-1,922	2,414
2	-0,139	-0,111	0,241	-2,984	2,541
3	-0,049	-0,080	0,527	-6,147	8,110
4	-0,337	-0,192	1,594	-18,166	19,341
5	-0,378	-0,145	1,159	-12,032	13,080
6	-0,086	-0,086	0,136	-1,926	1,523
7	-0,237	-0,215	0,135	-2,248	1,120
8	-0,321	-0,339	0,218	-1,217	1,016
9	-0,245	-0,162	0,240	-1,501	0,250
Software	MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,191	-0,159	0,249	-1,681	0,847
2	-0,076	-0,086	0,308	-4,446	3,779
3	-0,265	-0,133	0,872	-8,163	7,514
4	-0,027	-0,133	1,066	-13,910	20,244
5	-0,476	-0,061	1,366	-8,400	7,297
6	-0,152	-0,138	0,133	-1,363	1,719
7	-0,123	-0,094	0,204	-2,800	0,728
8	-0,051	-0,033	0,323	-1,736	3,074
9	-0,190	-0,125	0,247	-1,622	0,630

The relative comparison between Photoscan and Pix4Dmapper reveals higher standard deviation on areas 4 and 5, as it does when Photoscan is compared with MicMac. These must be due to the presence of vegetation near the buildings, which introduced error on the orthorectification and building modeling on all software.

In RGB versus NGB comparison, other errors that have been noticed are in polygons 3, 4 and 5 due to their elevated standard deviation. This points to changes in building geometry and presence of vegetation using different wavelength.

All remainder areas presented errors around 10-20 centimeters, perfectly acceptable for the ground sampling distance and type of scene.

4.1.2. Quality Check

The overall quality of the orthomosaics from UTAD is very good, but a closer analysis reveals details in the mosaic that usually are not taken into account when comparing photogrammetric software.

A closer detail of building edges is an important aspect and Figure 69, Figure 70 and Figure 71 are representing an example of the key differences in geometric reconstructing in the final orthomosaics.

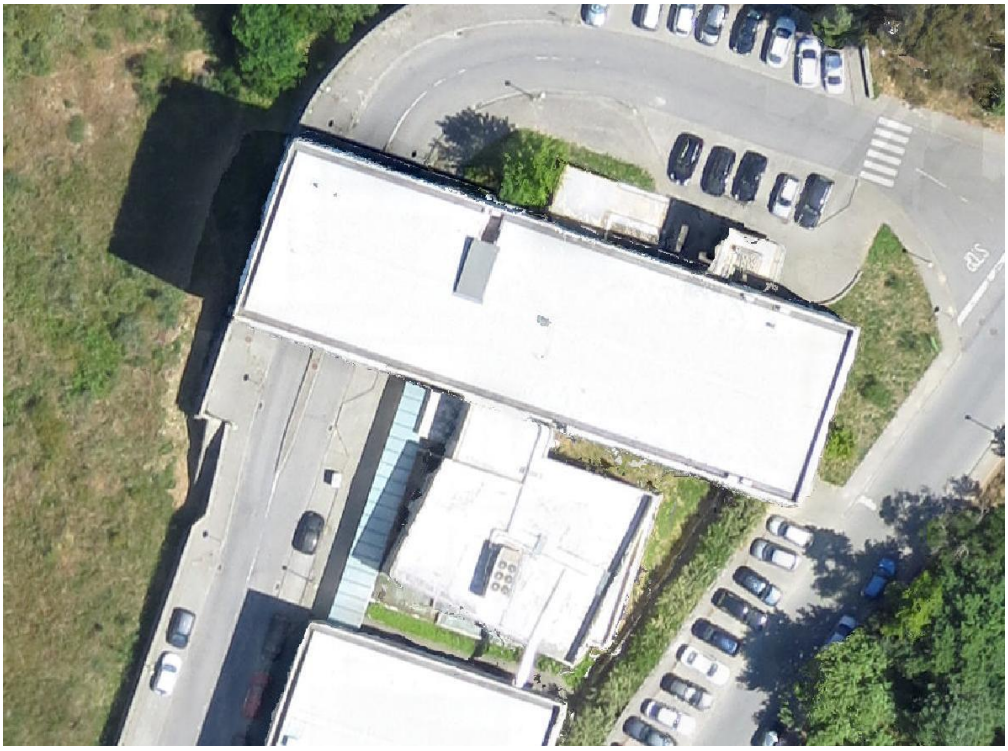


Figure 69 – Building detail from PhotoScan orthomosaic

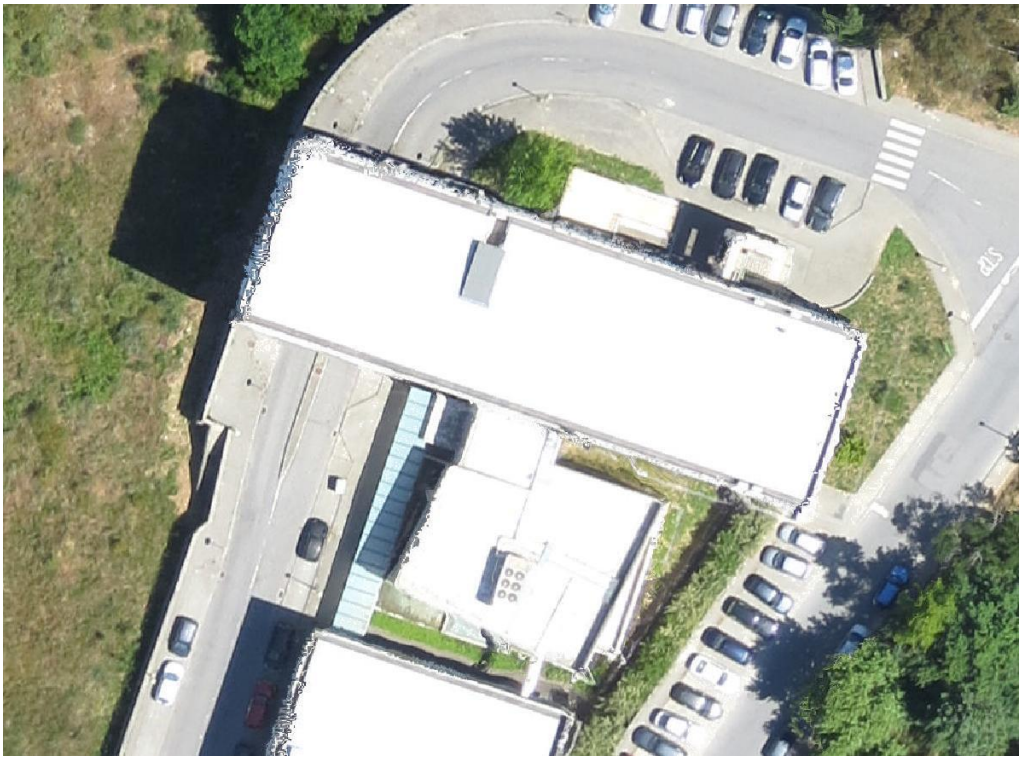


Figure 70 – Building detail from Pix4Dmapper orthomosaic

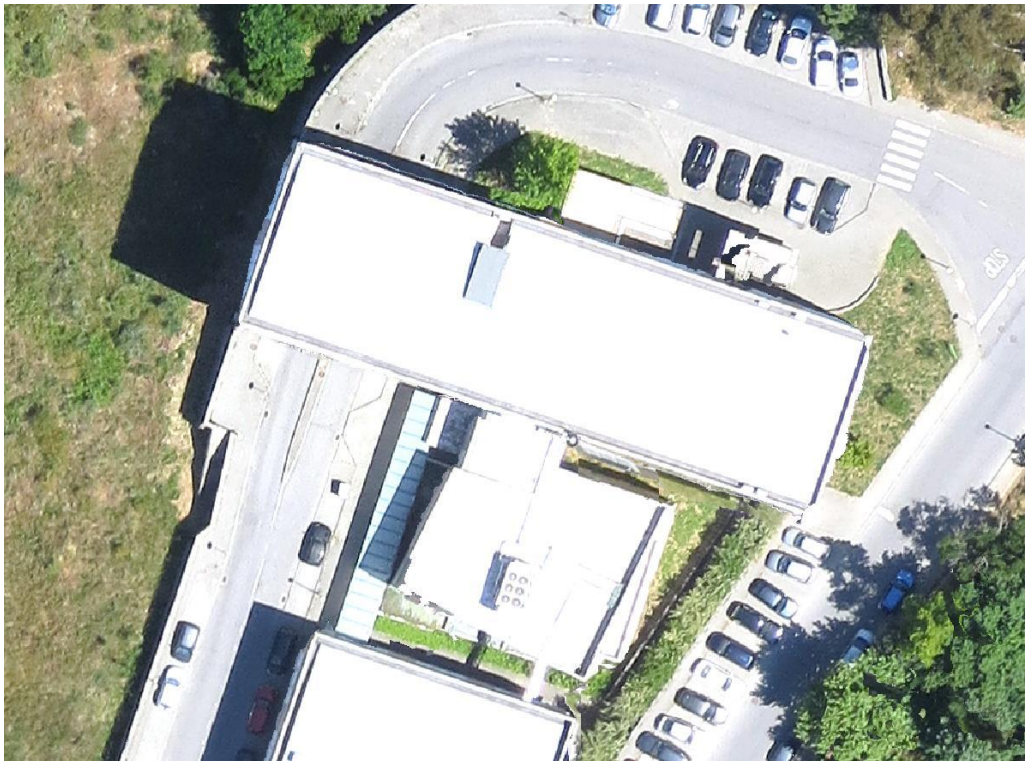


Figure 71 – Building detail from MicMac orthomosaic

Pix4Dmapper confirms the noisy building edges that were analyzed previously while the other two produce sharp edges. This noise presented in Pix4Dmapper can be

an issue when handling dense cloud classification and vectorization, failing to detect the building edges.

In radiometric equalization the commercial solutions offer a perfect result without noticing any cuts between images. MicMac, both in RGB and NIR imagery, does not handle so well the radiometric equalization, exemplified by the following Figure 72.

Figure 72 – Orthomosaic details from MicMac, a) and c) from RGB, representing a crop field and a football field; b) and d) represent the same in NGB imagery

The rough cuts are more noticeable, especially in fields and occasionally in some buildings. NIR imagery also revealed to be less affected by that weak point in MicMac. Several parameters were explored to avoid this kind of output but ultimately this was the best result. Some developers are already working to bring a new update in order to eliminate this common and know issue with this software.

Next, some profiles were made across a department building in UTAD and another across a vineyard and sports fields in the southern zone, and are represented in the following Figure 73, Figure 74, Figure 75 and Figure 76.

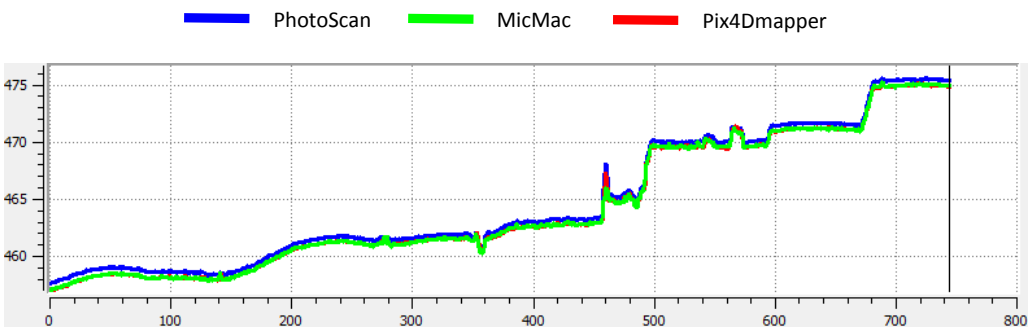


Figure 73 – RGB field profile from UTAD

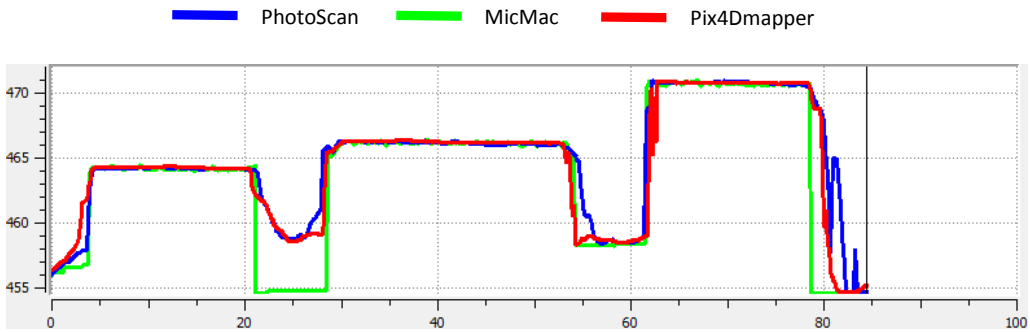


Figure 74 – Building RGB profile from UTAD

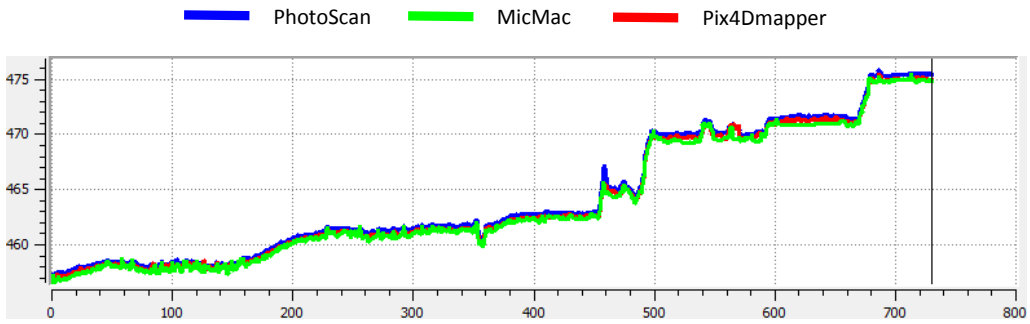


Figure 75 – NGB field profile from UTAD

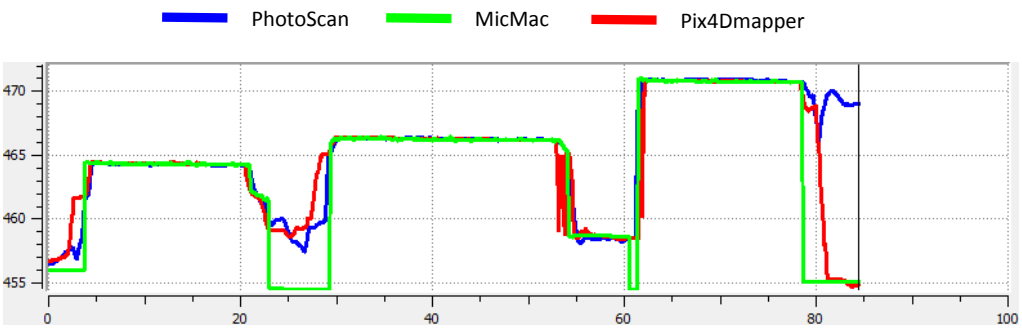


Figure 76 – Building NGB profile from UTAD

While the agricultural areas are basically the same in all software, MicMac has a very good verticality evidenced in both imagery, without being affected by near vegetation. This indicates that this solution has a better performance in urban areas and could be a good candidate to work with automatic classification and vectorization of dense point clouds, something that, for now, Pix4Dmapper is lacking.

4.2. River Douro Sandspit Data

The River Douro Sandspit is an important study area mainly for the presence of water in the images and obviously the monitoring of morphological changes in the body mass. The water has already interfered with the orientation of images and naturally it will produce errors in altitude, but that is not the region of interest and, in this case, is important to verify the ground precision and accuracy, to validate the orthomosaic and models output from the various software in order to help the coastal monitoring. Due to the conditions of light in the day of image acquisition, radiometric equalization proves very difficult and will be explored in this section.

Composed mainly of sand and with very few natural or artificial markers, the relative comparison was not performed in this area due to the lack of well-defined objects that could be used for markers. Therefore, only differences in products with GCP and without GCP were calculated, represented in Table 15 and Table 16.

Table 15 – Absolute comparison values, for River Douro Sandspit, between each software, with GCP

With GCP (6 check points)									
	PhotoScan			Pix4Dmapper			MicMac		
Coordinate	Mean (m)	Std. Dev. (m)	RMS (m)	Mean (m)	Std. Dev. (m)	RMS (m)	Mean (m)	Std. Dev. (m)	RMS (m)
X	0.027	0.047	**0.051**	0.079	0.082	**0.109**	0.003	0.041	**0.038**
Y	-0.040	0.029	**0.048**	-0.059	0.033	**0.066**	-0.013	0.036	**0.035**
XY (norm)	0.061	0.038	**0.070**	0.107	0.074	**0.127**	0.049	0.017	**0.051**
Z	0.090	0.065	**0.108**	0.090	0.065	**0.108**	0.069	0.122	**0.131**

Once again, MicMac reveals to be the most reliable in planimetric accuracy, with a Root Mean Square (RMS) error below Ground Sampling Distance (GSD) (5cm), distinguishing itself from the other commercial solutions. Pix4Dmapper in this case had a worse performance, with high planimetric error, even higher than in altitude. The small number of GCP used in Douro River Sandspit could explained this difference from Pix4Dmapper in the ground plane, but also the altimetric errors across all software, all within the same range of values, around 11-13 centimeters. This is a large area with very few noticeable features, contributing to the homogeneous nature of the scene, making it more difficult for the software to process. The lighting conditions also played a role on the origin of the errors, making it difficult to visually identify the GCP marker's centers. The implementation of more than the 6 GCP would be advised in order to achieve a higher density mesh of ground truth points and decrease the errors in altitude, parameter which is crucial to understand the displacement of sand and volumetric calculations.

Table 16 – Absolute comparison values, for River Douro Sandspit, between each software, without GCP

Without GCP									
Software	PhotoScan			Pix4Dmapper			MicMac		
Coordinate	Mean (m)	Std. Dev. (m)	RMS (m)	Mean (m)	Std. Dev. (m)	RMS (m)	Mean (m)	Std. Dev. (m)	RMS (m)
X	0.360	3.535	**3.247**	0.106	0.080	**0.129**	0.182	0.149	**0.227**
Y	-0.344	3.276	**3.010**	-0.792	0.062	**0.794**	-0.721	0.114	**0.729**
XY (norm)	4.013	2.049	**4.428**	0.803	0.052	**0.804**	0.752	0.145	**0.763**
Z	-7.972	4.427	**8.938**	-3.487	0.177	**3.491**	-3.268	0.130	**3.270**

The processing without GCP revealed again an extreme similarity between Pix4Dmapper and MicMac results, only four centimeters away in XY RMS with an impressive error of around 0.7-0.8 meters, further supporting the hypothesis of both using the same kind of processing in their core. PhotoScan produced errors of about 4 to 5 meters, expected in this kind of georeferenced images, while the other two handled

very well the scene and produced final products with decent precision, even for this type of processing.

4.2.1. DEM Analysis

The statistics of the whole representation of the region of interest were calculated by zonal statistics, in Table 17, and the histograms and the colormaps of the differences between models (Figure 77, Figure 78, Figure 79, Figure 80, Figure 81 and Figure 82), gives some insight over tendencies present on the models.

Table 17 – DEM difference statistics of River Douro Sandspit

	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
PhotoScan-Pix4Dmapper	2,117	1,139	3,505	-18,787	32,310
PhotoScan-MicMac	2,117	1,150	3,648	-22,135	46,619
Pix4Dmapper-MicMac	-0,461	0,000	5,328	-76,100	25,725

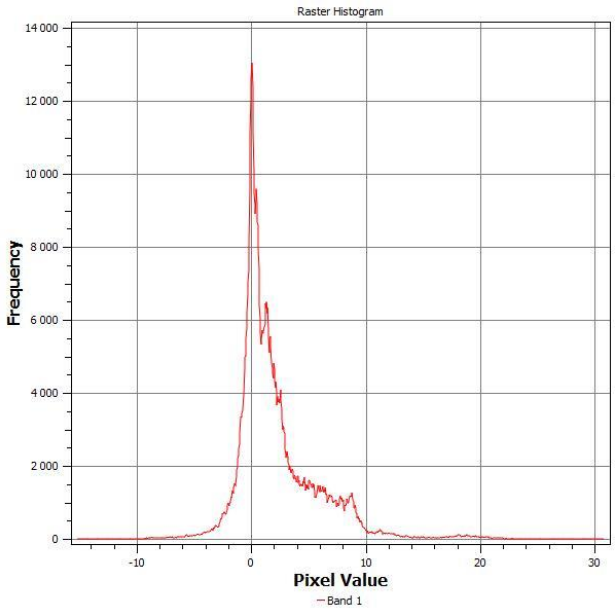


Figure 77 – DEM difference histogram from PhotoScan-Pix4Dmapper

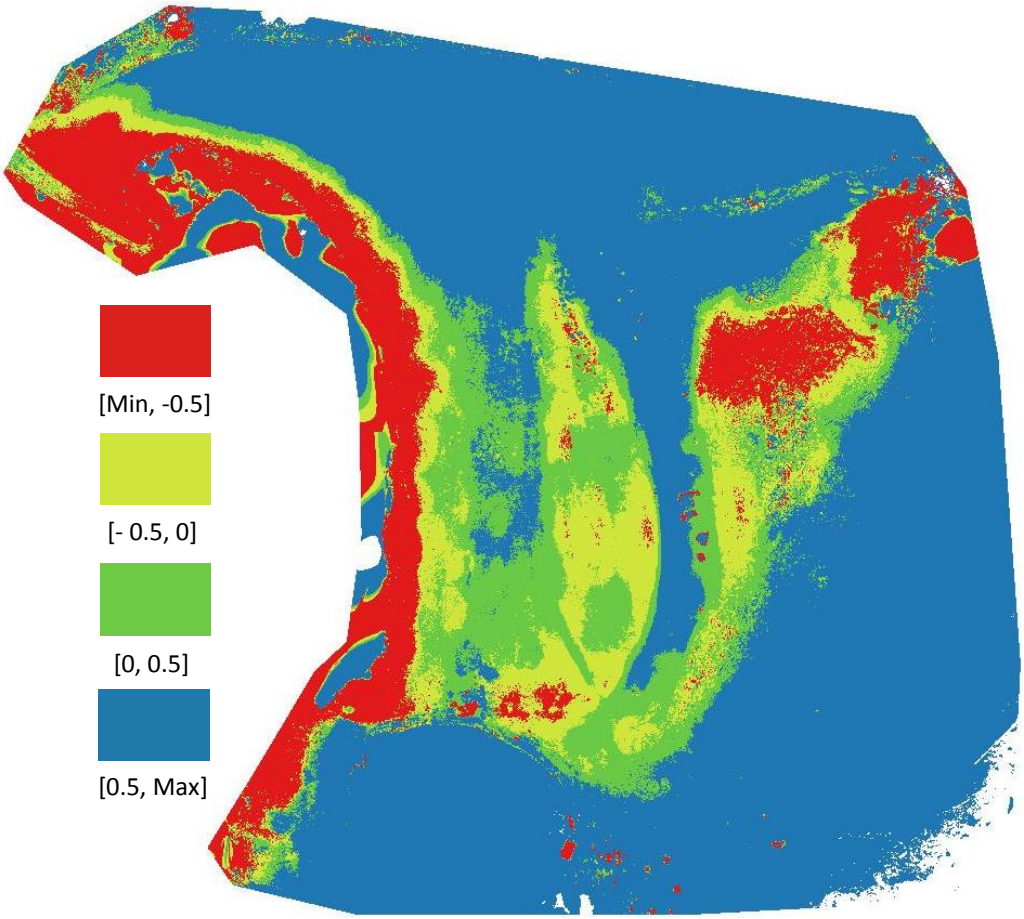


Figure 78 – Colormap of DEM differences from PhotoScan-Pix4Dmapper

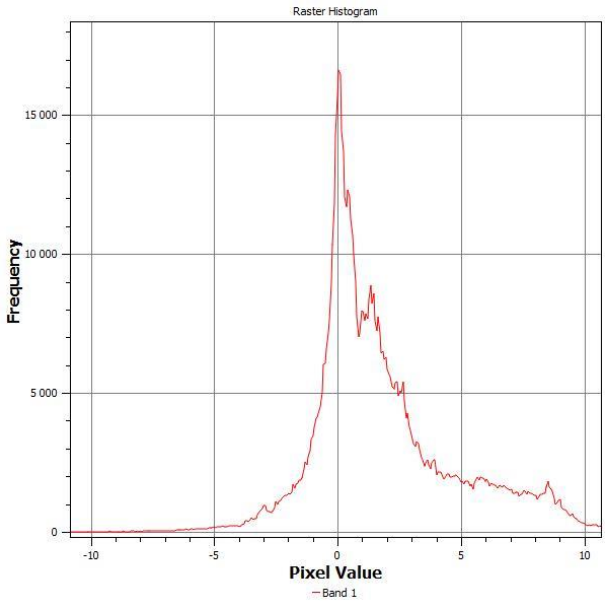


Figure 79 – DEM difference histogram from PhotoScan-MicMac

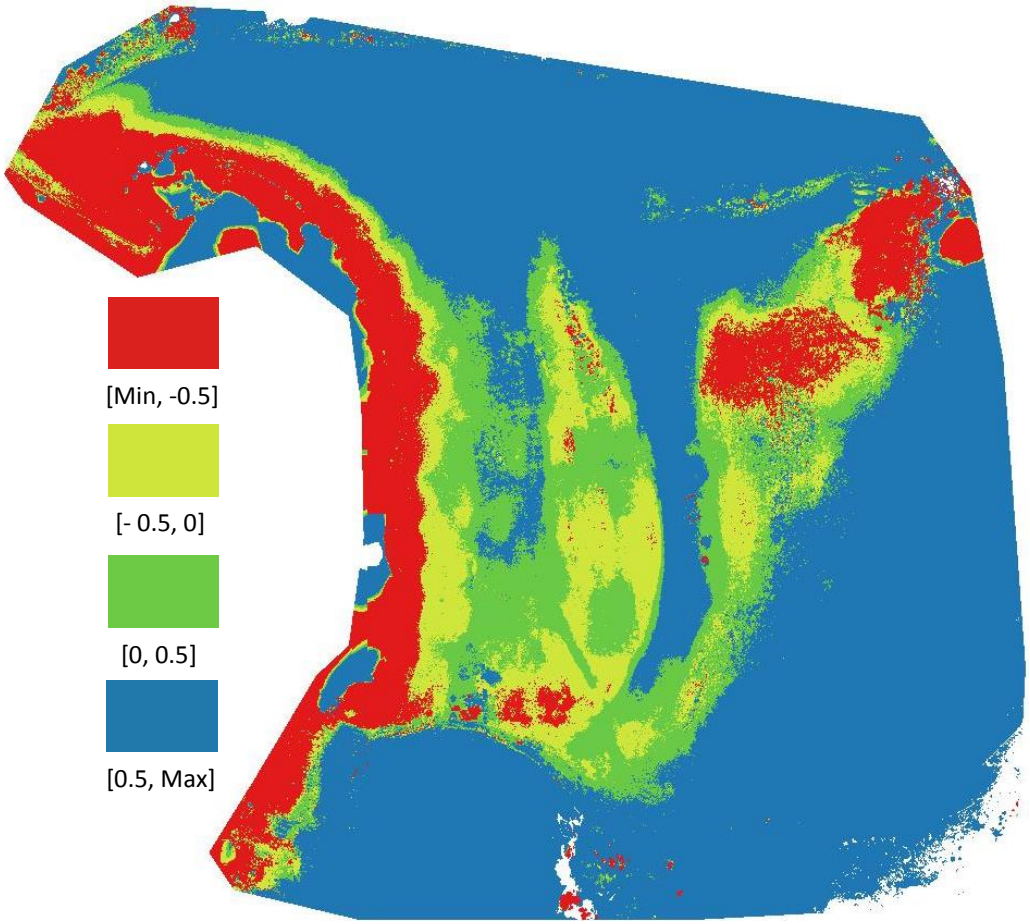


Figure 80 – Colormap of DEM differences, from PhotoScan-MicMac

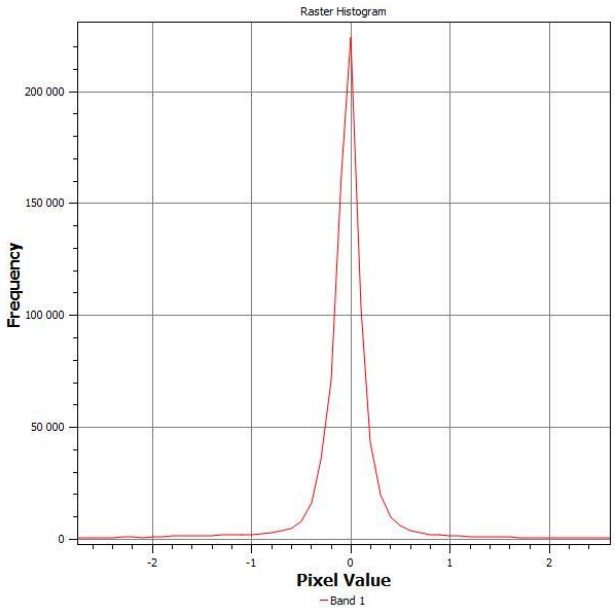


Figure 81 –DEM difference histogram from Pix4Dmapper-MicMac

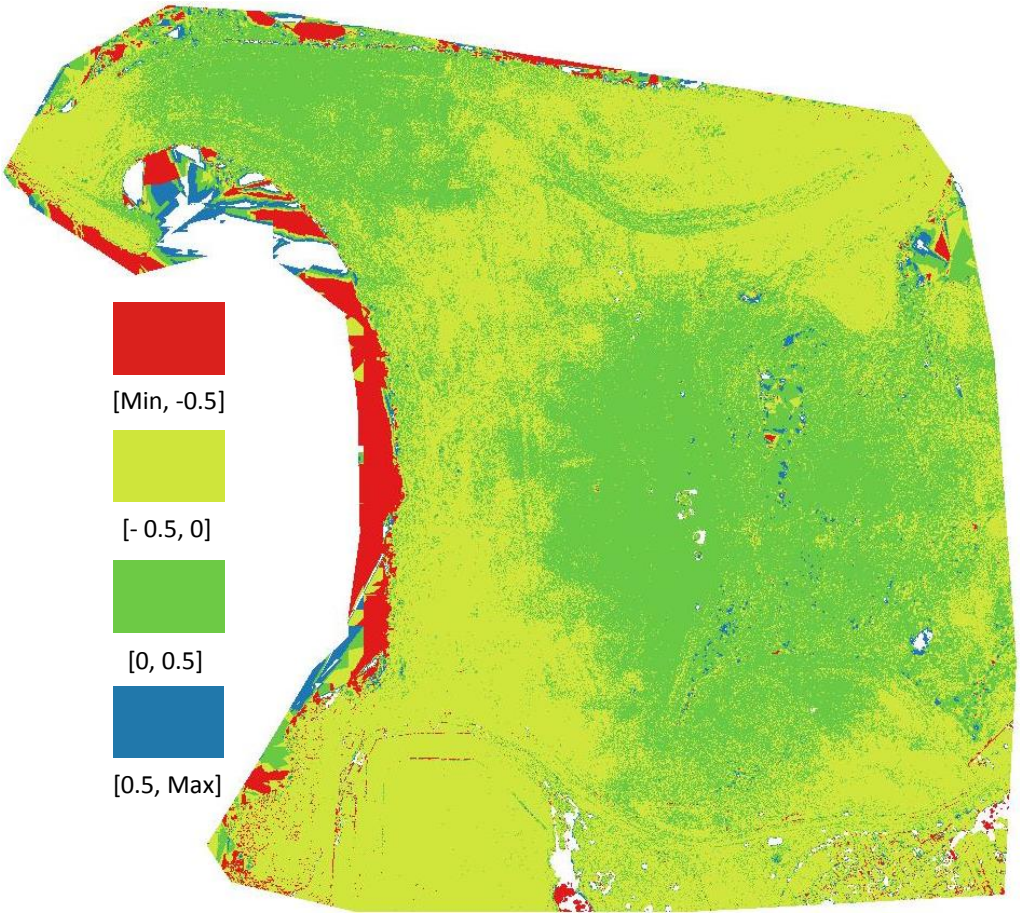


Figure 82 – Colormap of DEM differences, from Pix4Dmapper-MicMac

With statistics computed over the whole area, is natural that those values suffer the influence of errors produced on water zones. This is only a first contact with the data and the expected results would be a tendency of errors around 0 and a Gaussian distribution would indicate a similar model. In fact, the difference to PhotoScan produces some very strong positive values, with a mean difference of 2.117 and a median of 1,139 and 1,150 against the other two software, which results from the big differences near water on the west side and generally bad modelling through the whole scene, especially near water.

The differences between models were calculated and are presented in Figure 78, Figure 80 and Figure 82. The most noticeable aspect of these colormaps, is that the Pix4Dmapper-MicMac differences are in the range of green and yellow, only presenting higher values on near-water zones (which represent areas that are more prone to produce errors).

Another aspect to notice is that, although the other two models present a great similarity, looking at the Table 15 with the checkpoints analysis, Photoscan and Pix4Dmapper have the same RMS, mean and standard deviation on altitude, which goes against the colormaps that represent large areas with variations of more than 0.5m between Photoscan-Pix4Dmapper and Photoscan-MicMac. These unconformity of values might have origin on the position of the checkpoints (Figure 19) that are close to the GCP, meaning that the errors are smaller near those points, contradicting the colormaps. Referring to the histograms, once again Pix4Dmapper and MicMac produce identical signature, and the difference between them outputs a perfectly shaped histogram, centered in 0 with normal distribution, the ideal case of error distribution.

After those results, more GCP were added in place of check points but only in PhotoScan processing. This time the newly processed DEM from PhotoScan was compared against the previous results with only 6 GCP. The newly processed results are named PhotoScan_2, while the other will be PhotoScan_1, represented in Table 18. The histograms and colormaps of the differences between models are presented in Figure 83, Figure 84, Figure 85, Figure 86, Figure 87 and Figure 88.

Table 18 – DEM difference statistics of River Douro Sandspit with the new PhotoScan processing

	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
PhotoScan_1-PhotoScan_2	-1,983	-1,051	3,379	-32,083	22,211
PhotoScan_2-Pix4Dmapper	0,134	0,090	0,933	-15,228	23,993
PhotoScan_2-MicMac	0,134	0,084	1,225	-23,308	34,211

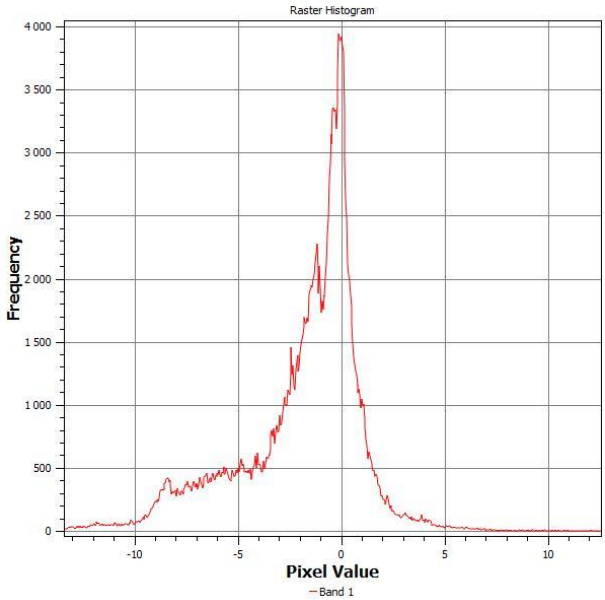


Figure 83 – DEM difference histogram from PhotoScan_1-PhotoScan_2

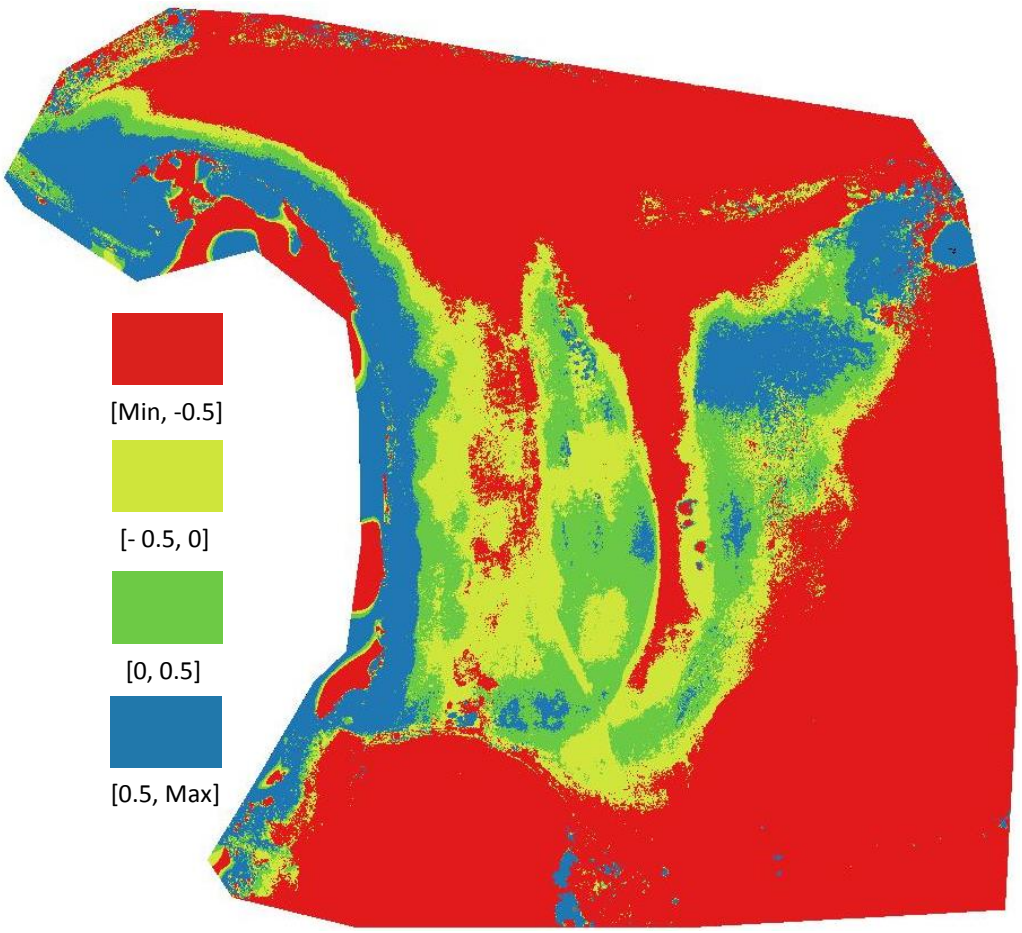


Figure 84 – Colormap of DEM differences, from PhotoScan_1-PhotoScan_2

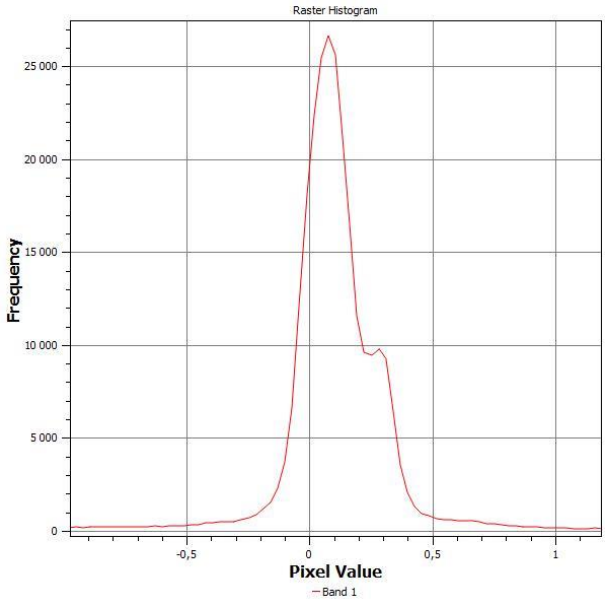


Figure 85 – DEM difference histogram from PhotoScan_2-Pix4Dmapper

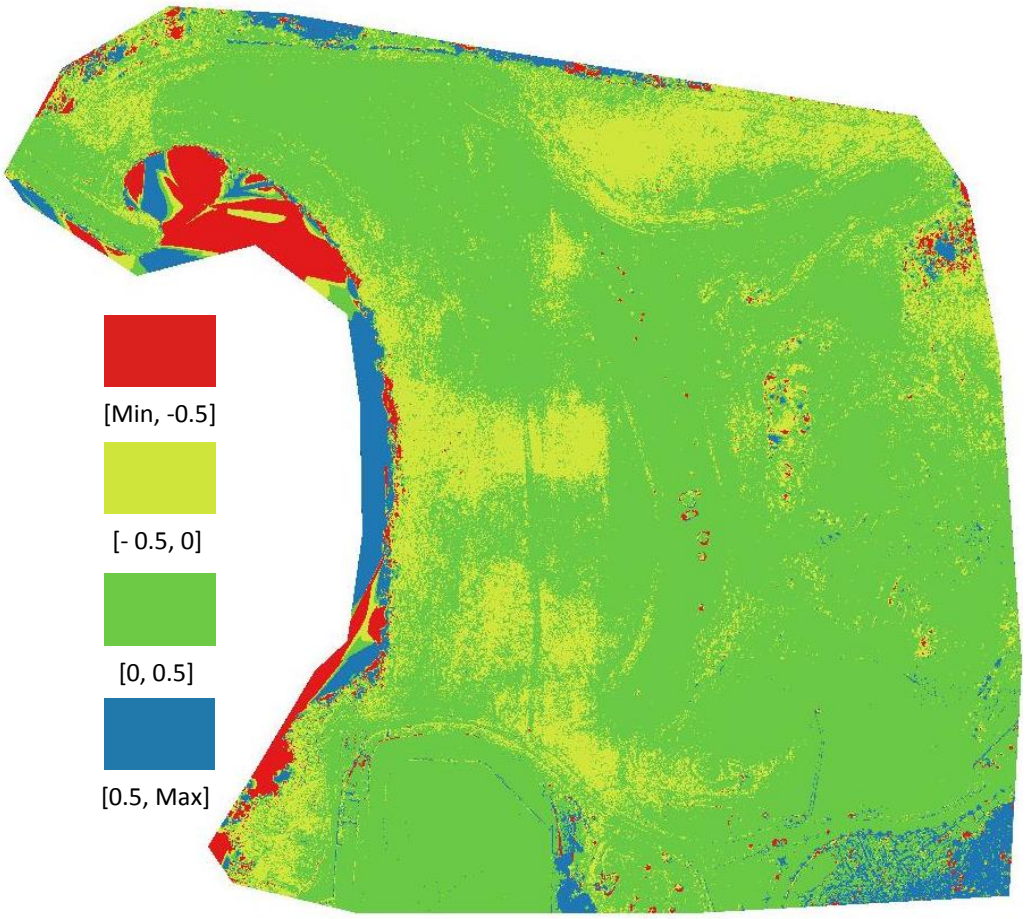


Figure 86 – Colormap of DEM differences, from PhotoScan_2-Pix4Dmapper

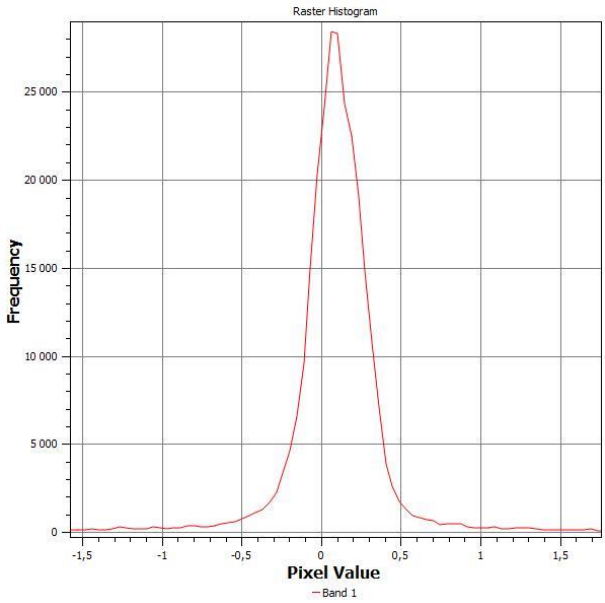


Figure 87 – DEM difference histogram from PhotoScan_2-MicMac

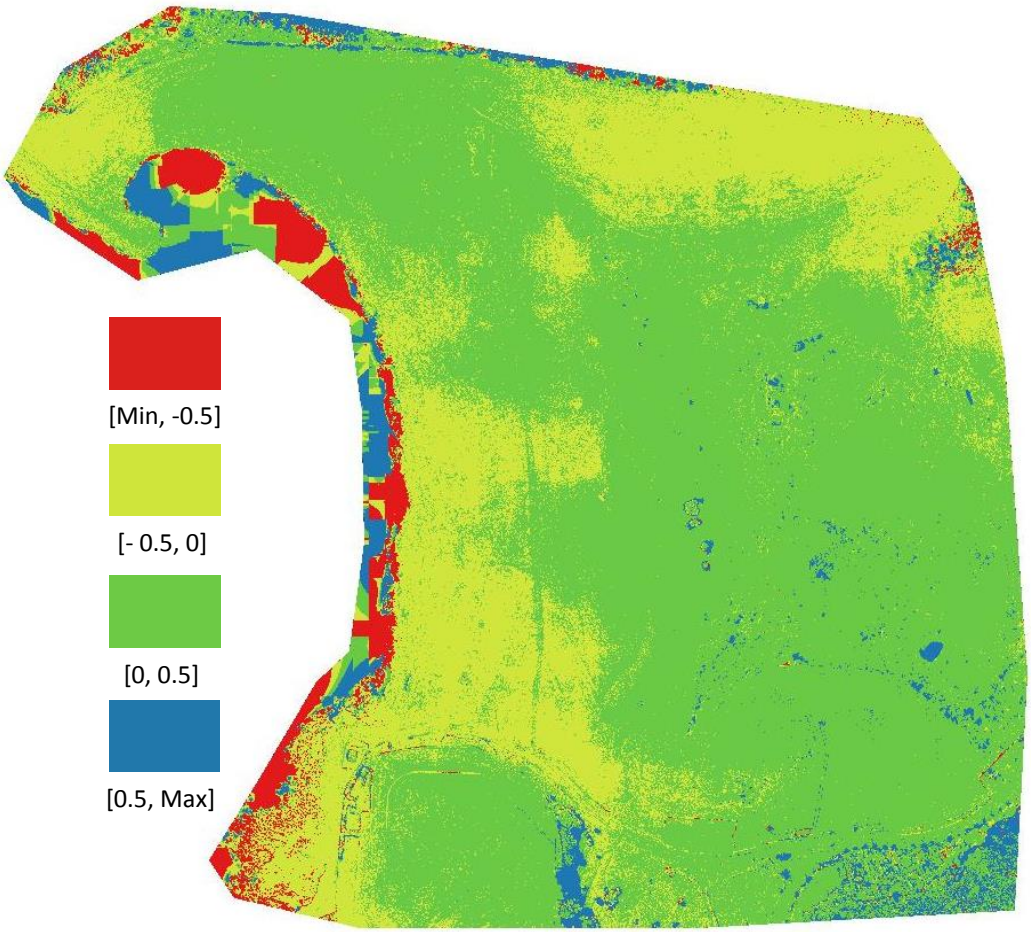


Figure 88 – Colormap of DEM differences, from PhotoScan_2-MicMac

These results indicate that the previously computed products from PhotoScan were badly modelled, while the other two software had a great performance with less GCP, generating accurate elevation models. This event could hint for some kind of difficulty for PhotoScan to deal with coastal areas or in this case a very homogeneous scene, although it was corrected with added GCP.

The smaller zones for statistic computing were created in locations across the entire area, displayed in Figure 89.

Figure 89 – Location of the chosen areas for detailed statistics, on River Douro Sandspit

Table 19 – Statistics for the chosen areas, on RGB imagery, of River Douro Sandspit

Software	PhotoScan_1-PhotoScan_2				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,017	-0,028	0,303	-3,274	1,735
2	-1,669	-1,763	0,612	-2,784	1,450
3	-0,330	-0,288	0,491	-2,919	3,035
4	-0,971	-0,786	0,704	-3,270	1,112
Software	PhotoScan_2-Pix4Dmapper				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	0,013	0,010	0,054	-1,007	1,020
2	0,111	0,112	0,050	-0,496	0,585
3	0,048	0,052	0,086	-2,573	1,358
4	0,092	0,100	0,056	-0,625	0,649
Software	PhotoScan_2-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,039	-0,039	0,070	-1,365	1,436
2	0,139	0,136	0,063	-0,580	0,690
3	0,051	0,053	0,084	-1,757	2,797
4	0,032	0,038	0,062	-0,419	0,626
Software	Pix4Dmapper-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0,052	-0,042	0,063	-2,368	1,158
2	0,027	0,021	0,038	-0,599	0,803
3	0,003	0,001	0,084	-1,206	3,801
4	-0,060	-0,063	0,069	-1,077	0,977

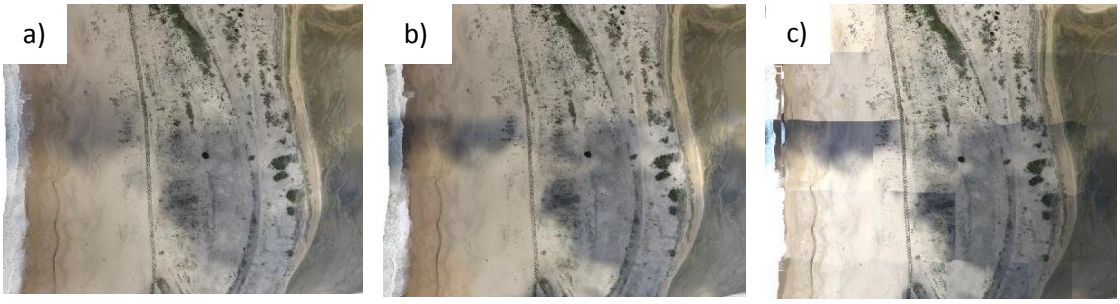
The variations on these smaller zones corroborates previous results, indicating that Pix4Dmapper and MicMac produce similar models. Both models from Zones 1 and 3, composing the central body, have the smallest differences between every solution, being smoother areas that are naturally less prone to bigger variation. On the other side, in zones 2 and 4, purposely located in critical regions, represent the areas where most of the changes are depicture, but still with mean values between 11 to 14 cm. The mean difference around 1.67 and 1 meters respectively in both versions of PhotoScan proves again the bad modelling that occurred with few GCP.

By the histograms, colormaps and statistical analysis, it has been noticed that Photoscan has some difficulty processing this coastal zone, needing more GCP to achieve the same accuracy as the other solutions with only 6. The MicMac-Pix4Dmapper comparison produced a normal distribution, indicating similar geometric reconstruction, confirmed by the colormaps produced.

4.2.2. Quality check

On this scene, the quality check will only focus on the radiometric equalization of each solution. As it was referred on chapter 3, the light conditions were poor, due to the variable presence of clouds, resulting in shadows or overexposing. (See Methodology).

On the Figure 90 we have 3 representations of the same scene, computed by the software in study. These particular set of images shows, in detail, the shadows effects on the mosaic's radiometric equalization. Firstly, on Agisoft Photoscan, it's possible to see the cloud's shadows, but are a little more faded out than the others. In Pix4Dmapper it's more noticeable the contrast between sand and darker shadows. In these case MicMac produces the worst effect, not being able to homogenize the scene at all.



Photoscan Pix4Dmapper MicMac

Figure 90 – Detail on radiometric equalization, from each software

As seen in Methodology, the overexposure can also interfere with the equalization, being, once again, more prominently on MicMac. The Figure 91 shows that situation, on the peer area.

Figure 91 – Overexposure errors, from MicMac's processing

In water zones is also very noticeable, as seen in Figure 92, where is visible the squares on the image, that reflects the poor color correction of each orthophoto.

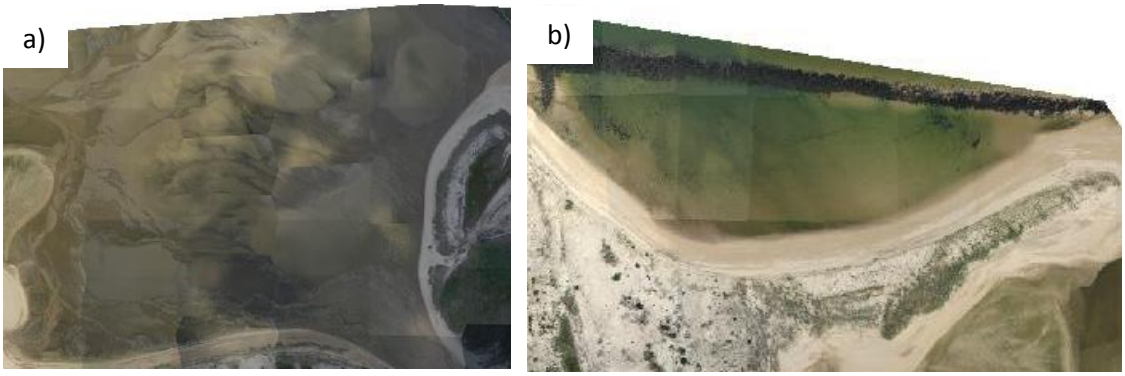


Figure 92 – Radiometric equalization errors, from MicMac's processing

Profiles made over the DEM indicates good geometric reconstruction from all solutions. Two profiles were calculated and are represented in Figure 93 and Figure 94.

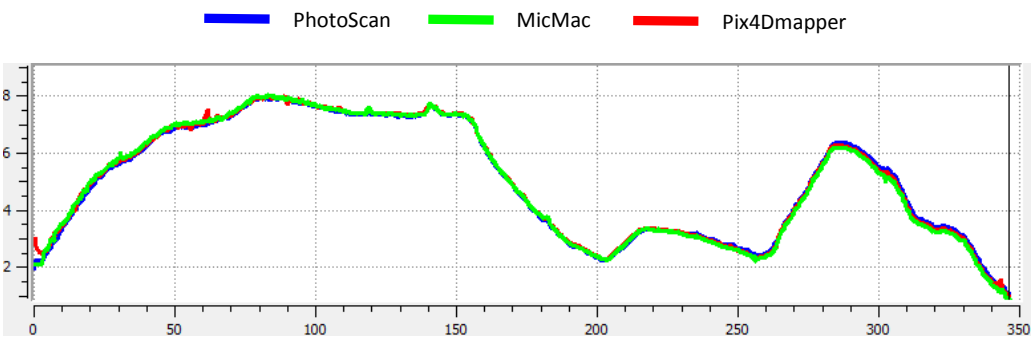


Figure 93 – West to East profile in Douro River Sandspit

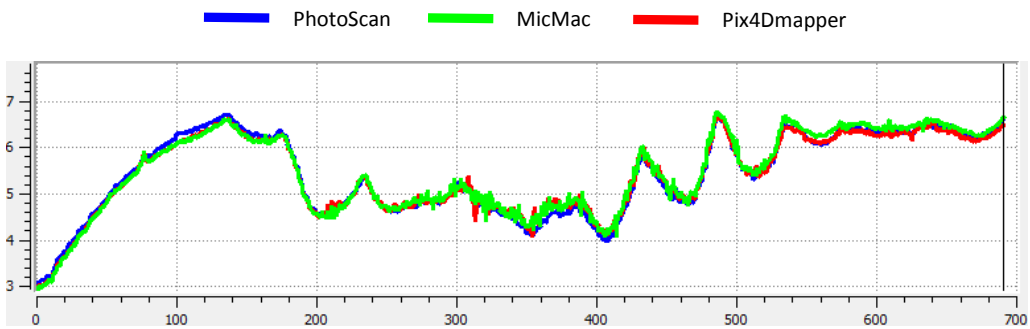


Figure 94 – North to South profile in Douro River Sandspit

The profiles corroborates the previous analysis, indicating a good modelling from PhotoScan with more GCP, and Pix4dmapper and MicMac achieving similar results with the initial 6 points.

Ultimately the discrepancies noticed in this case were corrected with more GCP, transferring check points to the georeferencing of the reconstruction. The new study revealed the good performance of Pix4Dmapper and MicMac in this difficult scene,

leading to the hypothesis that PhotoScan has some kind of difficulty dealing with coastal and homogeneous scenery, something solved with more ground control points.

4.3. Aguda Data

The Aguda beach near Espinho is similar to the previous area, but this time there is some urbanization factor, being a mixed coastal and urban scene. The water can be again a source of errors to the shore zones, but those are considered regions of interest to evaluate morphological changes.

Within this mixed scenery, comparison points were chosen in the urban area and some on the sand (where possible) and resulted in the Table 20.

Table 20 – Relative comparison values, for Aguda, between each software

Relative (10 comparison points)									
Software	**PhotoScan-Pix4Dmapper**			**PhotoScan-MicMac**			**Pix4Dmapper-MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.035	0.032	**0.047**	0.029	0.184	**0.177**	0.064	0.178	**0.180**
Y	-0.021	0.035	**0.039**	-0.056	0.123	**0.130**	-0.035	0.125	**0.124**
XY	0.048	0.040	**0.061**	0.113	0.198	**0.219**	0.112	0.198	**0.219**
Z	-0.033	0.425	**0.404**	0.008	0.374	**0.354**	0.041	0.079	**0.085**

On this scene, MicMac had the largest difference in XY, contradicting previous outputs. In fact, one of the points was in a zone badly mosaicked that introduced this very noticeable error. Therefore, this point was treated as an outlier and removed from the comparison. Thus a new statistic was computed in Table 21.

Table 21 – Relative comparison values, for Aguda, between each software, without the outlier

Relative without outlier									
Software	**PhotoScan-Pix4Dmapper**			**PhotoScan-MicMac**			**Pix4Dmapper-MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-0.035	0.032	**0.047**	-0.024	0.054	**0.057**	0.010	0.058	**0.056**
Y	-0.021	0.035	**0.039**	-0.017	0.034	**0.036**	0.003	0.026	**0.025**
XY	0.048	0.040	**0.061**	0.047	0.050	**0.067**	0.045	0.044	**0.062**
Z	-0.033	0.425	**0.404**	0.038	0.357	**0.341**	0.024	0.067	**0.068**

Now MicMac confirms the behavior observed in other case studies, and in this particular case, all software indicate a very good degree of similarity with the RMS value being almost the same in all three, indicating a good orthomosaic construction. Being a relative analysis that proves similar planimetric differences, it's indicative that, in these scene, all the software produced analogous results. The altitude differences reveal once again the resemblance between Pix4Dmapper and MicMac in their modeling process, while PhotoScan delivers greater differences to both solutions, something already verified on the other areas.

This survey was not part of this study and for that reason there are no check points available for the absolute comparison. Thus, only the statistics over processing without GCP was made, present in Table 22.

Table 22 – Absolute comparison values, for Aguda, between each software, without GCP

Without GCP									
Software	**PhotoScan**			**Pix4Dmapper**			**MicMac**		
Coordinate	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**	**Mean (m)**	**Std. Dev. (m)**	**RMS (m)**
X	-1.467	1.591	**2.119**	-0.266	0.055	**0.271**	-0.161	0.218	**0.264**
Y	-0.749	2.855	**2.844**	0.471	0.110	**0.483**	0.573	0.256	**0.623**
XY	3.257	1.460	**3.546**	0.549	0.075	**0.554**	0.618	0.287	**0.677**
Z	-4.135	2.280	**4.679**	1.702	0.744	**1.846**	2.273	0.742	**2.382**

MicMac and Pix4Dmapper revealed, like in Cabedelo, low planimetric errors, for a processing without GCP, while PhotoScan result is much greater than the other two, but still the average of this kind of processing.

4.3.1. DEM Analysis

It was calculated the zonal statistics for the region of interest, presented in Table 23, as well as histograms and colormaps of the variations between models of the 3 different software (Figure 95, Figure 96, Figure 97, Figure 98, Figure 99 and Figure 100).

Table 23 – DEM difference statistics of Aguda

	Mean (m)	**Median (m)**	**Stand. Dev. (m)**	**Min (m)**	**Max (m)**
PhotoScan-Pix4Dmapper	0.382	0.150	1.288	-12.438	19.988
PhotoScan-MicMac	0.438	0.162	1.435	-17.513	19.507
Pix4Dmapper-MicMac	0.056	0.014	0.779	-17.819	16.876

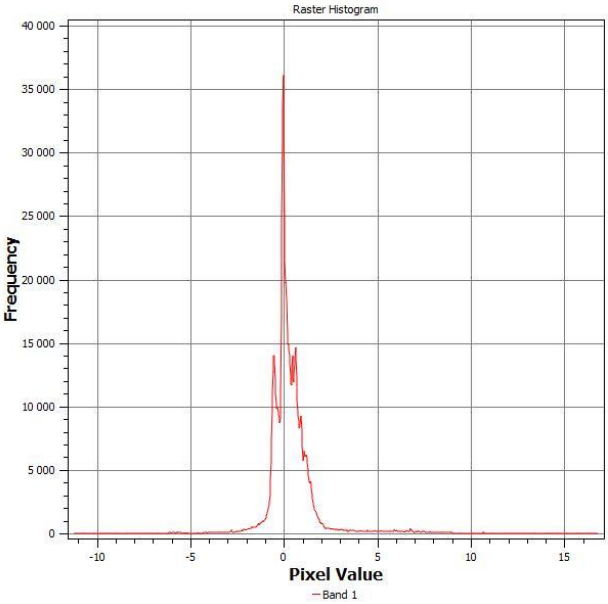


Figure 95 – DEM difference histogram from PhotoScan-Pix4Dmapper

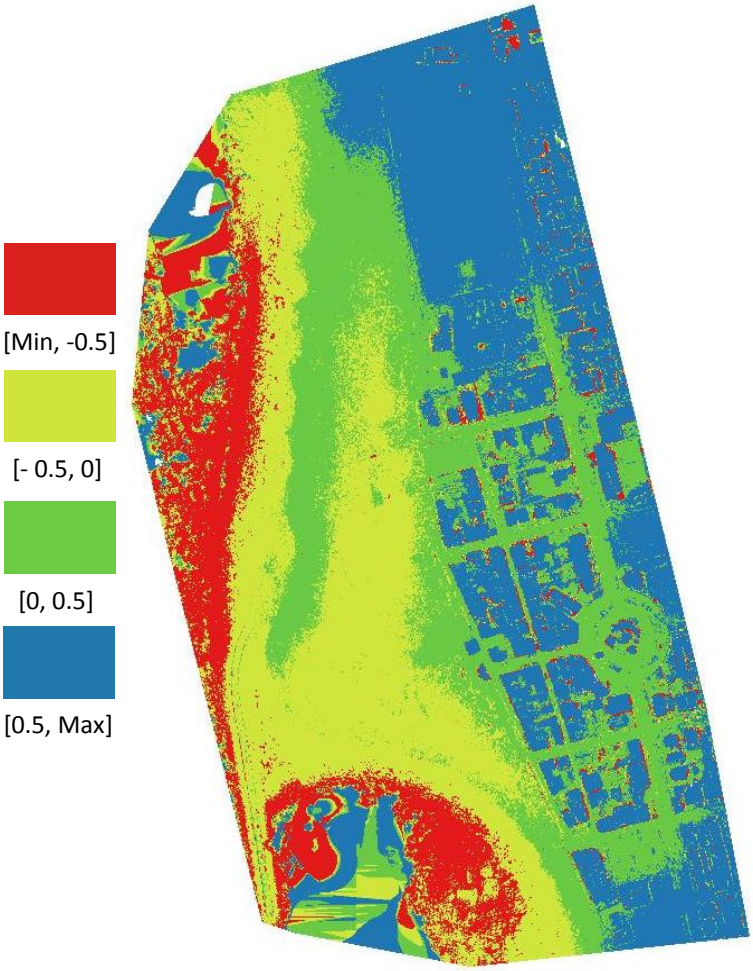


Figure 96 – Colormap of DEM differences, from PhotoScan-Pix4Dmapper

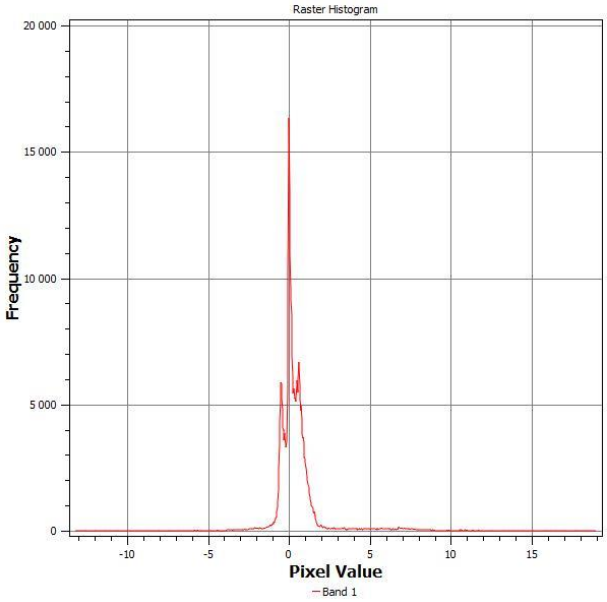


Figure 97 – DEM difference histogram from PhotoScan-MicMac

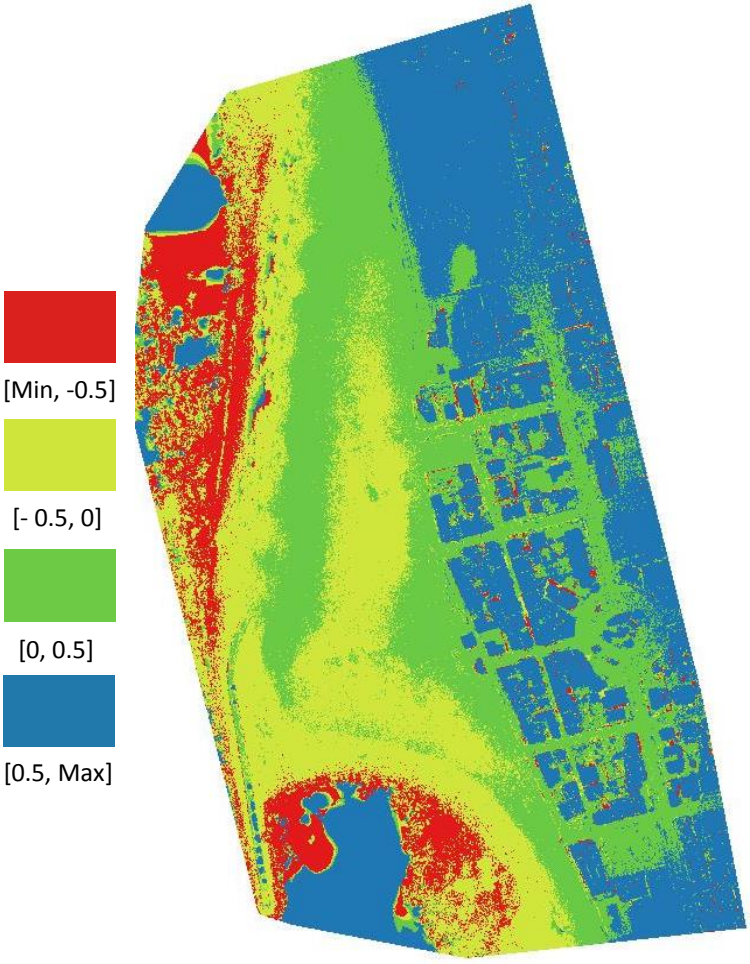


Figure 98 – Colormap of DEM differences, from PhotoScan-MicMac

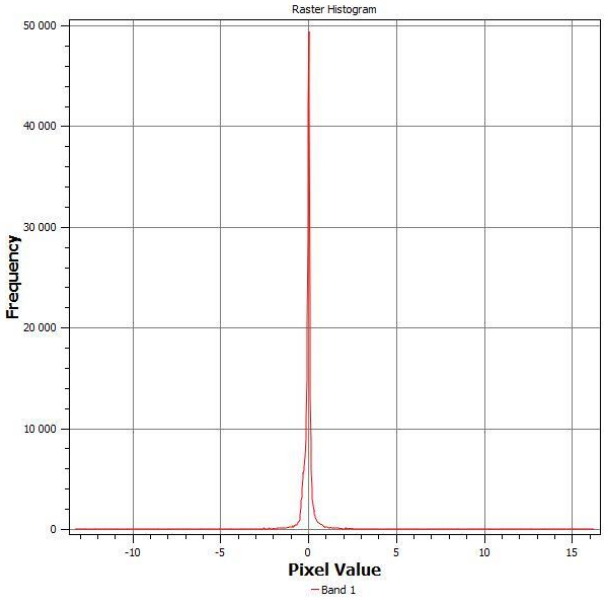


Figure 99 – DEM difference histogram from Pix4Dmapper-MicMac

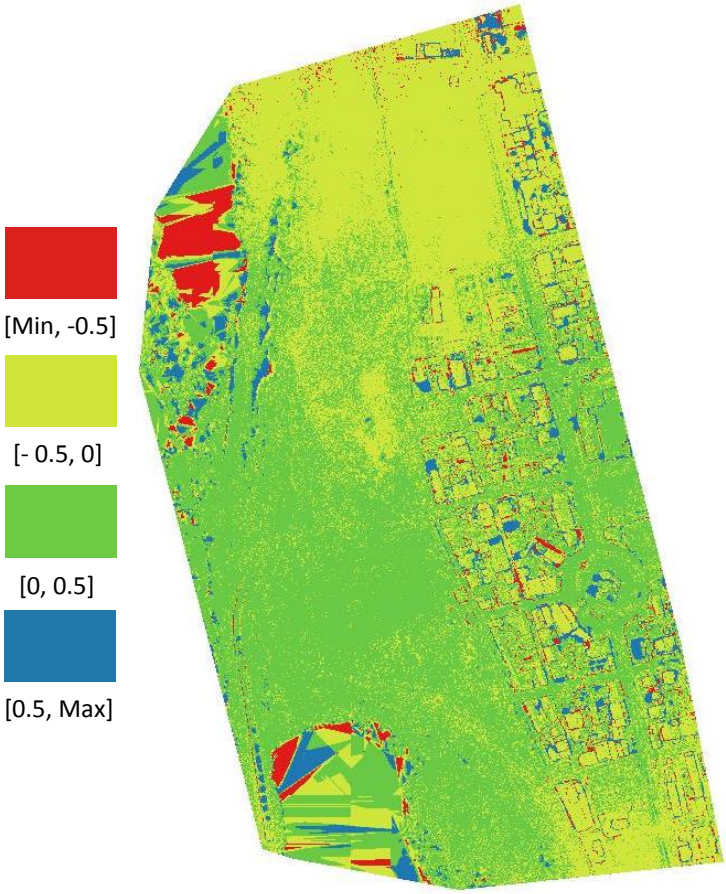


Figure 100 – Colormap of DEM differences, from Pix4Dmapper-MicMac

Analyzing Table 23, it's clear that the standard deviation is smaller with the Pix4Dmapper-MicMac comparison. The histograms show very strong negative and positive values that are explained in the colormaps by water and urban area differences, thus producing the values presented on the table.

Again, there's the obvious resemblance of Pix4Dmapper and MicMac, producing small variations on altitude. The real change for this particular case, is that Photoscan's comparison with the others, reveals much larger errors on the habitational area, specifically on the buildings, than on the beach itself. Actually, on the streets and sand, the variations are smaller, indicating that when presented with a mixed scene, Photoscan processes the tall objects differently than the other photogrammetric solutions. To verify this with more detail, 4 different zones were chosen to apply the same statistics calculations as before (Figure 101 and Table 24).

Figure 101 – Location of the chosen areas for detailed statistics, on Aguda

Table 24 – Statistics for the chosen areas, on RGB imagery, of Aguda

Software	PhotoScan-Pix4Dmapper				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0.032	-0.023	0.129	-1.790	0.732
2	0.296	0.298	0.047	-0.050	0.491
3	0.751	0.754	0.122	0.332	1.145
4	0.838	0.864	0.776	-6.951	9.692
Software	PhotoScan-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0.032	-0.023	0.129	-1.790	0.732
2	0.296	0.298	0.047	-0.050	0.491
3	0.751	0.754	0.122	0.332	1.145
4	0.838	0.864	0.776	-6.951	9.692
Software	Pix4Dmapper-MicMac				
Polygon ID	Mean (m)	Median (m)	Stand. Dev. (m)	Min (m)	Max (m)
1	-0.032	-0.023	0.129	-1.790	0.732
2	0.296	0.298	0.047	-0.050	0.491
3	0.751	0.754	0.122	0.332	1.145
4	0.838	0.864	0.776	-6.951	9.692

Clearly zones 3 and 4 output the largest differences across all software as they are inserted in areas without GCP placement and more difficult to process. Once again an extreme similarity from Pix4Dmapper and MicMac, with a low mean value for urban difference, although the standard deviation indicates great variations, probably from building edges were MicMac proved to be superior.

The positive variation from the colormaps will be further investigated with profiles in the urban area.

4.3.2. Quality Check

Presented in Figure 102, Figure 103 and Figure 104 is the same urban area to identify changes in building edges in each software.

Figure 102 – Building detail from PhotoScan orthomosaic

Figure 103 – Building detail from Pix4Dmapper orthomosaic

Figure 104 – Building detail from MicMac orthomosaic

PhotoScan is the best commercial software in this urban modelling but still producing some rough edges. Pix4Dmapper seems to be the worst with some ghosting effects projected on the road and general edge noise. Finally, MicMac outputs the best building edges despite some noticeable errors still present.

The commercial solutions generally produced good radiometric equalization throughout the entire orthomosaic, something that MicMac keeps failing like in previous study areas. In this case, visible in Figure 105, is obvious the failed color correction in the water and in some cases in the sand. This was already verified in Douro River Sandspit, but this time the sand produced a good mosaicking, direct result of the optimal lighting conditions of this day, with cloudy sky, avoiding sand overexposure.

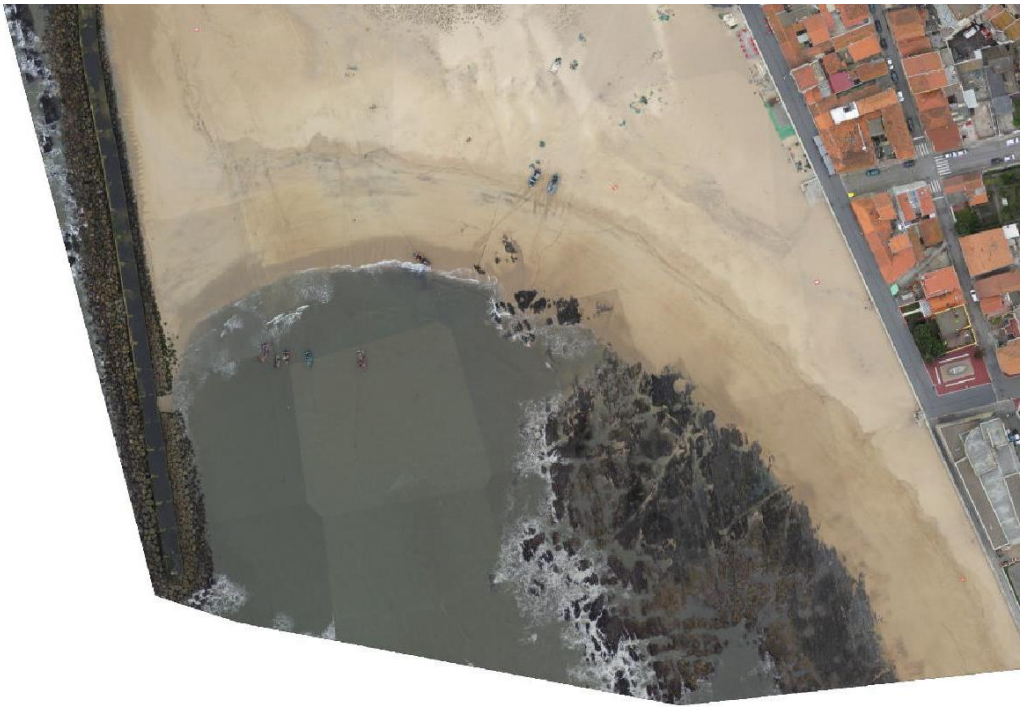


Figure 105 – MicMac radiometric equalization error in water

Two profiles were calculated over each DEM and produced the Figure 106 and Figure 107. The first profile was made across the sand from the water until the start of urban area, covering the whole beach from west to east.

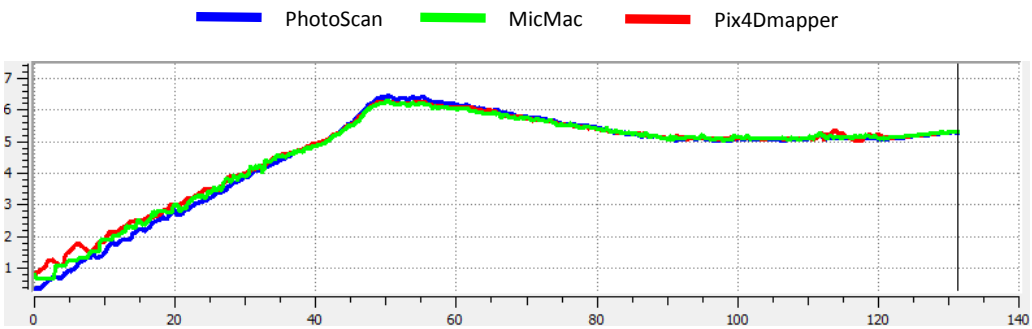


Figure 106 – West to East profile of Aguda beach

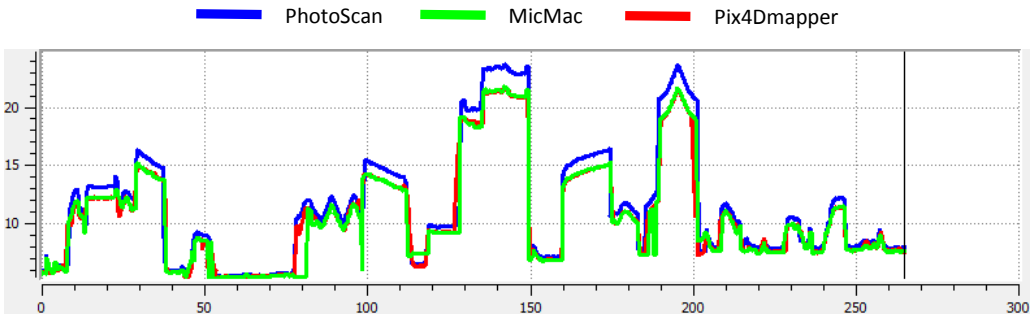


Figure 107 – Small urban area profile in Aguda

From the profile over the sand is clear that all solution achieved an overall good reconstruction, with obvious drift near the water. The urban profile was over a small area in the urban zone and explains the previous results from colormaps, indicating that PhotoScan modelled the city building heights with higher altitude than the other two, while the roads remained at same altitude in all software.

As there is no information over the specific height of buildings there is no way to know if PhotoScan exaggerated the building tallness, caused by lack of GCP and already observed coastal processing difficulties, or the other two dealt poorly with this zone.

A possible solution would be the use of a total station in order to measure some building heights in this study area, although it would be difficult to find the right spot to measure both locally and in the DSM.

5. Conclusions

Photogrammetry and software witnessed serious developments in recent years, both in commercial and open source, bringing these very specific tools almost into the everyday life of many people. Several businesses and universities took the advantage of this new wave of technological advancements to improve and innovate. This study intends to evaluate some of those solutions used in professional environment in several sceneries.

In the first study area, UTAD, images from both optical and near infrared were used with the purpose to investigate differences in processing from any software. In fact, PhotoScan seems to handle well both kinds of imagery, if they have GCP. It was found that with the version tested, PhotoScan had camera calibration and nonlinear distortion errors due to NIR imagery. MicMac revealed to be best in both planimetry and altimetry with both cameras, when GCP were used, followed closely by Pix4Dmapper in RGB.

In this area was observed that GCP placement was not ideal, not distributed evenly throughout the scene, resulting in bad terrain modelling from MicMac and Pix4Dmapper in the southern zone, even more accentuated on the NIR with open source. This was explained by the possibility of both software using same processing methods and using data from the georeferenced images with more weight than their own terrain reconstruction. It was corrected with the placement of more GCP and more Check Points for more statistical weight and again MicMac has the best results in planimetric and altimetric values. Ultimately the major changes that the different wavelength introduced into the results were the building geometries and added vegetation.

A key aspect that Pix4Dmapper fails is in building edges, being contaminated with a lot of noise, something that MicMac and PhotoScan can deal better, even more in MicMac when DEM profiling show extreme vertically on building limits and not being so affected by near vegetation.

The second study area, Douro River Sandspit, was a challenging area because the lighting conditions during the survey interfered with the processing, more noticeable in MicMac with serious radiometric errors while commercial software handle very well those conditions, slightly better in PhotoScan. The number of GCP was a crucial aspect to attend as PhotoScan produced a bad modelled DEM, a direct result of GCP number and placement. With more GCP PhotoScan produced a similar elevation model as the other solutions but at a cost of more control points. The comparative analysis previously revealed big differences in altitude, an aftermath of reconstruction variations with little

GCP placement. In planimetry MicMac was again the best solution next to PhotoScan, while this last software had a better altimetric result. To get an accurate altimetric error estimation, more check points are needed as they were all used during Photoscan processing. All software had some kind of interference from water, aggravating results on the shore.

The final area, Aguda, was used to demonstrate the potential of each solution in a mixed situation with a coastal area affected by water and with an urban zone. This time all software had similar result with a relative analysis being the only method of comparison, due to the lack of check points from this area. Later in the DEM analysis it was observed that the side without GCP, the urban area, produced great differences between PhotoScan and the other 2 solutions. On the urban profiling, building heights are distinct between them, with PhotoScan producing the tallest structures. MicMac was also the best in building verticality and edges by the detailed visual checking.

Overall MicMac was the best solution in planimetry and building modeling, overcoming commercial software, but lacking in cosmetic aspects with generally medium to bad radiometric equalization.

Both the open source and Pix4Dmapper suffered in geometry inside zones lacking GCP, while PhotoScan proved to be the strongest in geometric reconstruction even in those zones, meaning that PhotoScan can be considered the most robust and trustful by its good results. The River Douro Sandspit case seems to be the only one were PhotoScan did not perform as well as in the other scenarios, leading to the conclusion that this software doesn't perform so well in coastal and homogeneous areas.

All the results from every case study points that GCP placement is a key aspect to take into account when planning an accurate survey, as well the type of scenery, and ultimately the flight pattern as it was seen that it has some kind of influence in two of the solutions studied.

Another similarity found was the very little differences between Micmac and Pix4Dmapper models and planimetry without GCP, leading to the conclusion that some libraries or even coding are common. PhotoScan claims to have been built from scratch, which corroborates the results found during this study. Without GCP, MicMac and Pix4Dmapper have far better results, achieving sub meter precision, whereas the other commercial solution slightly drifts, and in NIR case, fails completely. NIR imagery also provided more vegetation information across all software and had little influence especially in PhotoScan and MicMac, using GCP, although the commercial one has poor performance in NIR without a good mesh of control points.

Ultimately the open source solution proved to be very efficient in producing good photogrammetric products, some with better features than commercial ones but with some disadvantages, mainly in the data and time spent to achieve those final products. During that analysis, while the commercial solution took almost the same time and data, with slight advantage to PhotoScan, MicMac on the other side generated huge amounts of data and significantly more time. Professionally, the data can always be bypassed with added hard drives, but longer processing times affects early work delivery.

Taking all this information into account, PhotoScan seems to be the best overall photogrammetric software, despite its flaws with NIR and coastal sceneries. The ease of use, processing options, time of processing, general robustness, imagery homogeneity and precision achieved across all studies.

Pix4Dmapper is a solution design for someone with no knowledge about photogrammetry to be able to operate, with a very basic interface to follow and with little control over the process. It achieves mostly very good results while in NIR not so much and with little extra processing time.

MicMac is a serious competitor, with some better features (excellent planimetric accuracy and building edges), result of a renowned developing institution and extremely qualified team. Ultimately is a good software to explore and understand every step of photogrammetric processing, giving the user full power over the processing workflow. Being open source also allows for customization for own projects and processing. Its major drawback are the huge data and processing time used by the software, and the bad radiometric equalization output in the final orthomosaics.

All software can be improved and known issues can be fixed, something that MicMac promises to address in their radiometric equalization, definitively one of the weakest points. Even Pix4Dmapper, after the conclusion of this study, launched an update that seems to fix the noise in building edges. This ever evolving state of software only brings benefits to users. With constant update and new algorithm developments, can make the difference during processing, pushing forward to improve upon previously difficult scenes to process.

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