COMPLEMENTARITY OF TERRESTRIAL LASER SCANNING AND DSM FROM AERIAL PHOTOGRAPHY: THE EXAMPLE OF THE CATHEDRAL OF AMIENS

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Abstract:

As every year, the ten students of the PPMD master's degree (Specialized Master's in Positionning, Photogrammetry and Deformation Measurement) of the French ENSG (Ecole Nationale des Sciences Géographiques), started their degree course last October with close-range photogrammetry fieldwork, which makes them practise every phase in the design, acquisition and processing of georeferenced data, within the stimulating context of a real project. They had a welcome opportunity to contribute to a long-term multidisciplinary project on the prestigious site of the almost thousand-year-old cathedral of Amiens, a royal town 140 km north of Paris. The ENSG team was in charge of surveying the southern arm of the transept of the famous cathedral at high-resolution. Since this monument is complex and full of different levels of detail (from large and rather flat walls up to very finely sculpted ones), it was necessary to use different and complementary techniques: topometry, terrestrial laser scanning, terrestrial and aerial photographic survey. The students returned to the ENSG with an interesting dataset to work on during the academic year. The scientific and cultural aspects of this innovative project greatly increased their motivation, making them particularly careful about everything taught in the field. ENSG teachers have been working on this data regularly since their return from the field, aiming to produce a full 3D model from both aerial and terrestrial data. As for their colleagues in Amiens, they were not only provided with a complete survey of the project area, but also with a group of reference methods to carry out the remaining survey operations.

1. INTRODUCTION

1.1 Fieldwork for ENSG students

As every year since its creation in the year 2000, the ten students in the PPMD master's degree *(*Specialized Master's in Positionning, Photogrammetry and Deformation Measurement*)* at the French Ecole Nationale des Sciences Géographiques (ENSG), started their degree course in October 2010 with a ten-day close-range photogrammetry fieldwork project, which makes them practise every phase in the design, acquisition and processing of georeferenced data, within the stimulating context of a real project. This type of life-size project is not only pedagogically valuable for the students, but also for the professors, who need to be regularly confronted with new technological challenges, in order to keep their knowledge up-to-date. As for potential partners (architects, archaeologists, academics) for whom they generally work in this type of project, they are usually satisfied with the results [1].

1.2 Multidisciplinary project in Amiens

Most of these pedagogical projects are designed to be both informative and motivating, but this one probably even more. As a matter of fact, ENSG students had the great opportunity to contribute to a long-term multidisciplinary project on the prestigious site of the almost thousand-year-old cathedral of Amiens, the regional capital of Picardy, 140 km north of Paris (figure 1).

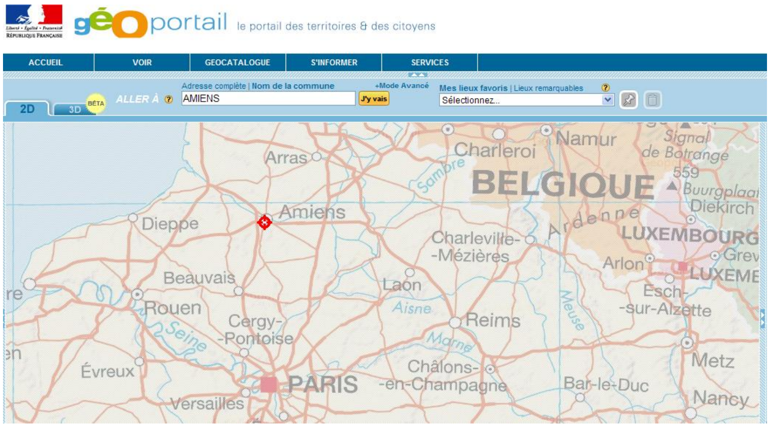


Figure 1.a : Situation map

1.b: Main facade of the cathedral of Amiens

There are many partners involved in this project: the Picardy Regional Direction for Cultural Affairs (DRAC), the Jules Verne University of Picardy, the city of Amiens, in collaboration with the ENSG, the Institut Géographique National (IGN), the Center for National Monuments (CNM) and the Ministry of Culture's General Heritage Division. This project is coordinated by a scientific board including the DRAC, the University of Picardy, the city of Amiens, and a team of archaeologists, historians and delegates from the diocesan commission. Firstly, this project aims to produce a detailed 3D digital model of the cathedral, which will gradually be integrated into the national digitalisation plan of the French Ministry of Culture, meant to facilitate public access to culture and cultural practices. Secondly, the project is supposed to produce a scientific documentary database, that is to say, not only 3D data, but also a variety of acquisition methods. Within the framework of this project, a preliminary survey phase was carried out from October 18 to 27, 2010 by the ENSG team, using various measurements techniques on the southern arm of the cathedral's transept.

2. SURVEY

2.1 The area

The project area had indeed to be limited, since available time on site was constrained by the students' schedule: only ten days for the fieldwork survey, and later, a few days for data processing. The Notre Dame cathedral of Amiens happens to be one of the most voluminous French cathedrals, comparable to the cathedrals of Paris, Chartres, Reims and Beauvais, which were built after the early Gothic age (around 1200). The cathedral of Amiens is remarkable because of its dimensions (145 m in length, 44 m to 122 m in height including the spire), and the richness of its interior and exterior decoration. An exhaustive description of the cathedral of Amiens would not fit into this article. It is worth mentioning at least the impressive western and southern portals (figure 2), which represent a spectacular combination of sculptures and statues representing scenes from religious history in a kind of medieval setting [2]. From whatever point of view, the observer admiring the cathedral always gets an infinite quantity of details to examine.

Figure 2: Detail of the southern portal

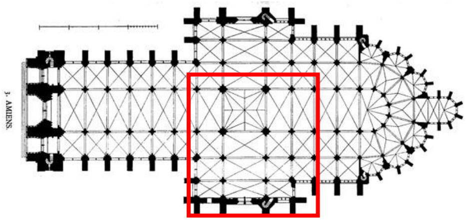


Figure 3: The project area (in red)

In order to be able to reach the objective, i.e. providing the project's scientific board with a consistent set of high-resolution 3D data and a variety of acquisition methods, the decision was made to work only on the southern arm of the cathedral's transept, and to leave the rest for future ENSG fieldwork, or for other private initiatives (figure 3). The general project objective was first converted by the ENSG into more detailed objectives in terms of expected products, which corresponded to different pedagogical workshops in the field.

2.2 The team

The ENSG team was made up of ten PPMD master's degree students, and five ENSG professors. In October, that is to say, at the very beginning of the academic year, the students have only basic theoretical knowledge in photogrammetry, topometry and GPS positionning. Moreover, not all of them have already had experience with these techniques in the field. Therefore, the team was far from being professional. But the pedagogical objective of the fieldwork was precisely to illustrate, in advance, in the field, the theoretical principles which would be taught during the academic year. As for the professors, all of them having a specific area of interest, they could help take up most of the technical challenges arising on such a monumental site.

2.3 Methodology in the field

A wide range of methods were adopted to work in the project area, in order to be faithful to its shape and aspect, including every part from the vast volumes under the vaults up to the thin corridors in the triforium, or to the delicate statues on the outer façade [3, 4]. Aerial data was also necessary to complete what could not be seen from the ground level [5, 6].

2.3.1 The equipment

Nearly all the equipment used during this project belongs to the ENSG (figure 4). For the topometric measurements made and their tying into the official French coordinate system, 7 total stations (2 Leica TCR803, 3 Leica TCR705, 1 Leica TCA1201, 1 Leica TCA2003) and 4 GPS (3 Trimble R8 and 1 Trimble NetR5) were used. The laser scanning was carried out with a Scanstation 2 from Leica. Aerial and terrestrial images were taken with two digital single lens reflex cameras : a Canon EOS 5D Mark I equipped with a 24-105mm zoom and a Canon EOS 5D Mark II equipped with different lenses of fixed focal lengths (35, 50 and 100mm). The lenses used were calibrated on the ENSG 3D calibration test field before or after the fieldwork.

Figure 4: Equipment used in the field

2.3.2 Topometric ground control point network

Two different levels of ground control point networks were required.

First of all, a primary permanent network was designed. The goal of this primary network is to support photogrammetry and lasergrammetry on their own ground networks and to allow further work on the cathedral (since this field campaign only concerns the southern arm of the transept). Permanent ground markers were set out but natural points, such as intersections of floor tiles, were also chosen due to considerations of conservation. The resulting network covers a larger area than the part of the building which was to be surveyed in order to facilitate future campaigns. The position of the points was chosen by giving priority to intervisibility between the stations. A detailed and rigorous definition of these points was documented by the students through identification sheets. This permanent network was measured with total stations. The link to the official French reference coordinate system, RGF93 (in a CC49 projection), and to the official altimetric system, IGN69, was determined by GNSS and levelling observations on three exterior points. In order to get the best possible precision from GNSS differential measurements, a permanent GNSS station had been previously installed on the roof of the university.

Second, this network was densified for the laser and image georeferencing. Specifications (position, type, number of points, accuracy) were defined according to the constraints of each technique. This secondary network was also measured by total stations from the previous primary control point network.

2.3.3 Terrestrial image shooting

As a basis, a classical photographic survey of the project area was carried out in order to produce:

- a complete archive of the monument,
- textures with good image quality (compared with laser scanner),
- documents, like orthoimages, for analysis.

Specifications were in accordance with requirements for traditional photogrammetric capture (minimum 60% overlap and 20% sidelap) with a few millimetres ground sample distance (GSD). Ground control points (artificial targets & natural details) were chosen and documented for image georeferencing. Through this acquisition, the students could fully understand the mechanism of a camera. They also improved their skills in stereoscopic shooting.

In addition and as a methodological test, panoramic images were acquired with the same point of view as the laser station (figure 5). The panoramic system, called “Panodeon” is developed by IGN’s MATIS research laboratory. The goal of this system is to have good image texture for the laser station. For the time being, the panoramic image is automatically produced by Autopano, which merges high dynamic range (HDR) individual images, without taking the correct geometry of the camera into account.

Figure 5: Laser scanner and Rodeon station on the same point + resulting panoramic image

Finally, specific photographic surveys for the generation of dense digital surface models (DSM) were made to study particularly interesting objects (mainly on sculptures). DSM can indeed be complementary to laser scanning since it offers very high-resolution point clouds. Figure 6 describes the configuration of this shooting. Two kinds of images are taken: the first group (in red) of images indicate a dense correlation (their positions are very close around one point of view); the second group of images (in green) are necessary to strengthen the orientation between images.

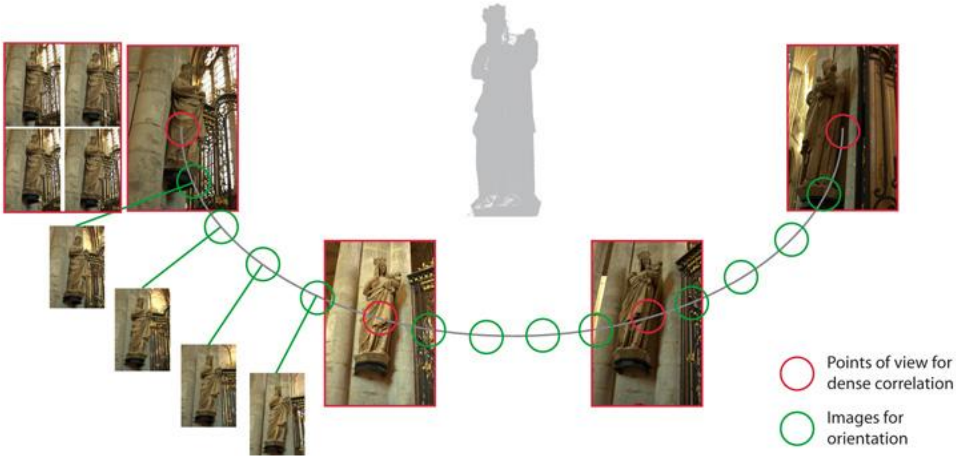


Figure 6: Example of image shooting for dense correlation ("*Virgin with child*")

2.3.4 Terrestrial laser scanning

The goal of terrestrial laser scanning is classically to obtain a complete 3D point model of the area. Since the project's scientific board wanted to create a 3D model from these points mainly for virtual reality, it was decided to adapt the resolution to the complexity of the object to describe (from a few millimetres to 1 or 2 centimetres). Finally, 23 laser stations (inside and outside at three different levels) were used providing 500 000 000 points.

To calculate the laser stations' georeferencing, artificial targets were defined as well as natural points (details chosen on the cathedral or from its environment) and scanned at a very high-resolution.

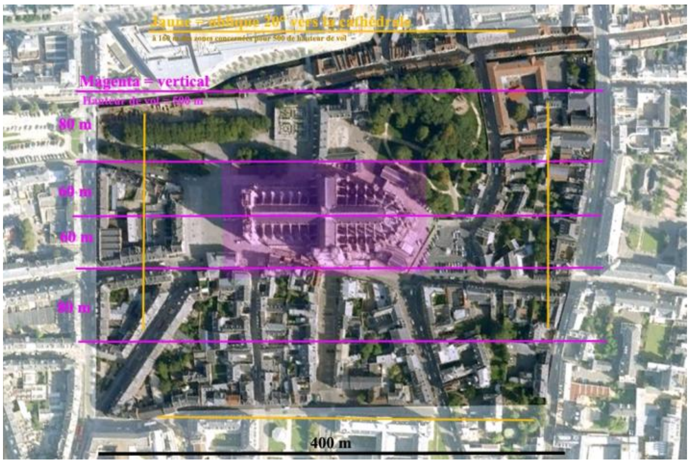
2.3.5 Aerial survey

ENSG has ten years of experience in aerial surveying, always with small or ultra light planes. The equipment used is generally very light: only a camera sometimes controlled with a laptop computer. Neither GPS nor INS is used. In this project, the aerial survey was necessary to acquire complementary information on the upper part (mainly the roofs) of the cathedral [5, 6]. Moreover, the scientific board thought it would be a good opportunity to survey the historical centre of Amiens and to localize the cathedral in its environment.

The expected product from these aerial images was a DSM generated by dense correlation. This DSM should complete the point clouds produced from terrestrial laser scanning, with equivalent specifications. Consequently, the aerial survey had to provide photographs with a very small ground sample distance (GSD) and a very high overlap (80/60%). Because of a compromise between civilian aeronautic rules and camera performance, the GSD was only around 3cm. An oblique aerial survey (by means of a second flight, giving a non-vertical viewing axis to the camera) was also carried out in order to densify image data, which would ensure better 3D reconstruction, and better textures on the facades. The specifications of the flight mission (altitude, distance between flight axes, frame rate) had been calculated by the students during their coursework at the ENSG.

The aerial survey was planned just before the fieldwork survey on October 15, 2010. Since ENSG did not have its own means, the school appealed to a private pilot from a neighbouring flying club, who had no particular previous experience in photographic surveys. The plane was not equipped with any kind of flight management system for this kind of work.

Flight altitude was around 550m and the camera used was the Canon EOS 5D Mark II with a 100 mm focal length. Vertical images (10 strips included 3 resumptions) and oblique images (15 strips) were finally produced with, in some cases, a non regular configuration due to difficult flight conditions (visual flight control, pilot's inexperience).



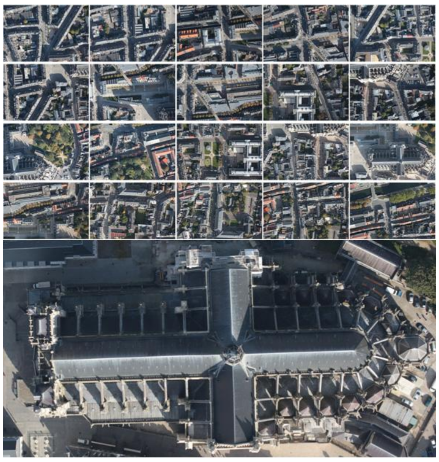


Figure 7.a: Expected flight lines **7.b**: Examples of vertical aerial surveys

The aerial survey was equipped with thirteen ground control points determined during preliminary stereopreparation conducted in the field for the PPMD project. This number of points was small due to the fact that no external data (GPS or INS system) was available, but significant overlaps would compensate this light network. Their coordinates were measured by GNSS in RTK (Real Time Kinematic) mode and most of these points were linked to the altitude system by levelling. They were finally integrated into the CC49 projection, so that they would be compatible with all the other data.

3. DATA PROCESSING

The ENSG students, especially the PPMDs, were implicated as much as possible in the data processing procedures.

3.1 Phase 1: Georeferencing

3.1.1 Topo calculation

GNSS calculations were carried out by Bernese GPS software. The 3D coordinates of all the targets and natural points chosen for further photogrammetric and laser operations were calculated from the primary network with Comp3D, a software program designed by IGN for global bundle adjustment in micro-geodesy and topometry. In order to improve the overall quality of these points, more observations from other stations were also integrated into the global calculation. The accuracy achieved on the primary network points was approximately 3 mm in planimetry, 1 mm in altimetry (the unit variance factor, sigma0, being equal to 1). As for the targets and natural points, their accuracy was about 5mm.

3.1.2 Laser georeferencing

In this project, a new method for laser georeferencing was tested, based on concepts similar to those in aerial triangulation: both ground control points and tie points were used in order to minimise topometric operations. It was essential here because of the complexity of the architecture and the short time allotted for fieldwork. Whatever their types, these points were scanned at very high-resolution and carefully documented. Ground control points were finally points from the primary ground control point network, specific targets for lasers, photogrammetric targets or natural details (secondary networks).

In the global adjustment for laser georeferencing, topometric observations (angles and distances) and laser observations (3D coordinates in the laser's local coordinate system) were taken into account at the same time. This method requires having an appropriate weighting which takes into account measurement accuracy and the type of points used (generally, natural points don't have as good a definition as artificial points). The final internal accuracy of laser georeferencing was around 3 mm and absolute accuracy was 5mm.

Terrestrial image georeferencing

Once shot and quickly validated in the field, the terrestrial stereoscopic images needed to be georeferenced. This phase was started in Amiens during the fieldwork without any automatic tools. As a matter of fact, since only a limited number of images were concerned (most project areas were covered by less than 15 images), the students could manually measure the ground control points and all the tie points, using Redresseur, a user-friendly software developed and provided by Y. Egels, a photogrammetry expert. This manual phase was also an opportunity to assess the images, as far as image quality and proper overlaps were concerned.
The georeferencing was calculated by TopAero, a software program developed by IGN, normally designed to calculate georeferencing of aerial images with the bundle adjustment method. Only a relative bundle adjustment was made in Amiens, because the topometric coordinates of all the ground control points were provided after the completion of the fieldwork. The final georeferencing was only added once back at the ENSG. It has not yet been formally checked with ground checkpoints, but an adequate number and distribution of both tie points and ground control points, combined with correct residuals (average image residual smaller than 0.5 pixels, average ground control points residual smaller than 1 cm) makes the team optimistic about the assessment.
Yet, one of the inside walls of the cathedral could not be processed successfully: despite many controls, the calculation with ground control points did not give acceptable residuals. A short investigation into the EXIF metadata showed that the camera parameters had not been properly set up during the photographic survey. Instead of keeping the zoom at a 24 mm focal length, as required, the operator probably unwittingly pushed it to a slightly greater value. The problem is, there is no way to find out precisely which value it was. Thus, the relevant calibration certificate, giving, in particular, the distortion value, cannot be established with traditional calibration procedures. Autocalibration should be investigated but the configuration (photographs with parallel axes of a flat wall) is particularly unpromising. For the time being, all the images suffering from this defect have been deleted from the regular processing.
This problem led to the conclusion that more data processing should be carried out during the fieldwork, so that inadequacies or errors during the acquisition phase can be highlighted in time to be caught and dealt with.

3.1.4 Aerial triangulation

Until now, only aerial triangulation of 142 vertical images (corresponding to 7 strips) has been calculated. Automatic aerial triangulation has also been carried out. Key points were generated with the traditional SIFT algorithm but a specific procedure, developed at MATIS laboratory, was used for multiple matching.

Finally, 2 422 tie points were created, around 180 per image with a high redundancy (some tie points are seen on 20 images). A traditional bundle block adjustment was calculated using TopAero software and gave the camera positions and orientations in the CC49 projection system. Image residuals globally correspond to expected values of around one pixel. Better image residuals could probably be obtained with a better calibration process: it is indeed difficult to correctly calibrate a camera with a long focal length on the ENSG calibration test field because of a lack of setback.

Until now, the absolute georeferencing has not the expected quality (which should be around 5cm): sigma-x = 23 cm, sigma-y=8 cm and sigma-z=90 cm. High residuals appear in the east part of the block where overlap values are inferior to specifications. In particular, the last strip has a very small sidelap and the residuals on the GCP are very high in this area. The GCP network was designed for specifications which could not be respected here. The low B/H ratio does not help either to reach the expected quality.

Adding oblique images should strengthen the block and probably will result in the expected accuracy, all the more so, as some strips are in transversal directions. ENSG is currently working on oblique image georeferencing. Despite this lack of absolute accuracy and since the relative orientation is correct, the work was pursued on DSM and 3D model generation to test the global methodology (see section 3.2.3).

3.2 Phase 2: Data production

3.2.1 Stereoplotting

The stereoscopic images covering the outside southern facade, divided into two strips, were used by seven first-degree course ENSG students, in the framework of their stereoplotting project. It is worth mentioning that these students had been trained for two years to use aerial photographs rather than architectural images.

Stereoplotting specifications were defined according to image resolution to include a lot of details, and to previous architectural stereoplotting of other cathedrals. Different codes were assigned to stone joints, statues, columns, stained-glass window panes, etc. The job had to be split into several zones which were shared out among all the students. The different zones could then be merged and completed. Differences in interpretation showed up at that stage, mainly due to lack of experience.

The resulting product is impressive, but not perfect (figure 8). This is mainly due to the fact that photographs were shot from the ground level only: the lowest strip was shot close to the facade with a 24 mm focal length, while the uppermost strip was shot from much further away with a 100 mm focal length camera. This caused differences in resolution and depth accuracy: the uppermost strip, in particular, suffers from a poor B/H ratio. Another potential problem is that there are still many hidden parts.

If the project’s scientific board turns out to be interested enough in stereoplotting products, specific elevation devices could be used to shoot the highest parts of the cathedral in future.

3.2.2 Orthorectification

Orthoimages were not explicitly requested by the project’s scientific board, which seemed to be only interested in “3D” at the beginning. Since ENSG professors wanted to make the students practise orthorectification in any event, they proposed delivering the resulting products with the other expected data. Cumulus, specific software written by Y. Egels, was used to calculate the orthoimages. As an input, Cumulus takes georeferenced images, triangulated georeferenced laser data, and the definition of a projection plane (figure 8). The output is an orthoimage at a predefined resolution, preferably chosen close to the resolution of the raw images.
Efforts were made to reduce the radiometric differences between consecutive images as much as possible in order to get a homogeneous result. For instance, the stained-glass windows, despite a very careful photographic survey, caused some unwanted reflections on the images of the cathedral’s interior which had to be eliminated as much as possible. It is all the more important since they were intended to be delivered to non-expert people, who would not consider an image with visible seam lines as a reliable product.

Figure 8.a: Stereoscopic images of the outside southern façade **8.b:** Stereoplotting on the outside southern façade **8.c:** Laser data on the southern facade **8.d:** Orthoimage

3.2.3 DSM generation

Terrestrial laser scanner provides high-resolution 3D point clouds and reliability very quickly. Yet, this technology is not always the most appropriate to produce these point clouds. It is, in particular, not easy to acquire data on the top of buildings. In the aerial context, the airborne lidar system is generally used to produce DSMs, but at very high costs. Moreover, technical performances (in terms of accuracy, resolution) are specific to each device and cannot be changed easily.

That is why images appear to be complementary to laser scanning for DSM generation. As explained before, in this project, images were used for this purpose in two cases:

- To get data on the roof of the cathedral
- To acquire very high-resolution 3D point clouds on interesting objects.

In both cases, the “Micmac” algorithm was used [7]. This dense correlation software was developed by the MATIS laboratory and can be used in different contexts (satellite, aerial, terrestrial imaging) by adjusting a set of parameters according to the case.

Figures 9 and 10 show DSMs produced with this Micmac algorithm from aerial and terrestrial images.

Since an aerial DSM is calculated from georeferenced images (see section 3.1.4), the 3D point coordinates are directly expressed in the CC49 projection system. This DSM has a 3 cm resolution according to the image GSD. But, since the aerial triangulation used here is not as accurate as expected (because it is not the final one), this DSM can only be used as a methodological test. Its quality has not been assessed until now and should be improved. Moreover, such kinds of DSM suffer from defects where the correlation is difficult, especially on the edges of the object (when the point of view is parallel to the object).

The terrestrial DSM was calculated in a local coordinate system with a non-metric scale, since, in this case, the Micmac algorithm was used in a self-calibration mode and no GCP had been chosen. To properly register this DSM, an ICP algorithm could be used on laser points, or the similarity transformation could be calculated with points selected from the laser data.

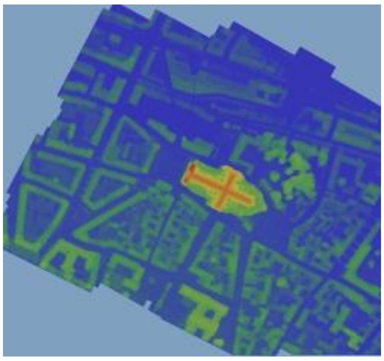


Figure 9: DSM from Micmac algorithm: general view on the cathedral

10.a: DSM from Micmac algorithm: general view on the “Virgin with child”

10.b: DSM from Micmac algorithm: zoom on the “Virgin with child”

A 3D city model was also automatically created in vector format from an aerial DSM, with BATI 3D software. BATI3D uses building footprints and a library of building types, to fill in gaps visible in the DSM [8].

4. TERRESTRIAL & AERIAL DATA FUSION, ASSESSMENT OF THE RESULTS

The methodology followed in this project implies that nearly all the data are intrinsically integrated into a common coordinate system (CC49): terrestrial laser stations, terrestrial images, orthoimages and aerial images. Terrestrial DSMs and panoramic images still need to be georeferenced in this common system.

Yet, the nature of this data is quite different and some discrepancies remain in the actual product:

- Resolution is insufficient in uppermost areas: aerial surveys with planes provide good quality images, easy to process, but with an insufficient resolution due to altitude limitations. Unmanned aerial vehicles (UAV) or balloons could fulfil these requirements,
- Absolute accuracy between data are largely different : improvement and corrections are needed on the aerial georeferencing,
- 3D points produced from laser data are more reliable than DSMs from images,

- 3D points produced from images have good RGB information. Laser point clouds could benefit from panoramic images, but fine georeferencing of this panoramic image has not yet been attempted.

From a pedagogical point of view, the objectives of the project have been fully reached: all the students practised most of the methods which were used in the field (topometry, GPS measurements, terrestrial laser scanning, terrestrial photographic surveys, panoramic photographic surveys). They returned to the ENSG with an interesting dataset to go on practising with during the academic year. The scientific and cultural aspects of this innovative project greatly increased their motivation, making them, in particular, pay more attention to everything that was taught in the field.

5. PERSPECTIVES

The southern arm of the cathedral of Amiens's transept was covered with various types of data : a primary point network to go on working in the same coordinate system, georeferenced terrestrial laser data at a resolution going from 5 mm for the remarkable details to 2 cm for flat walls, georeferenced aerial images at a resolution of 3 cm, georeferenced terrestrial images at a resolution of a few millimetres, a 3D model made from the aerial images, high-resolution 3D models on specific statues made from terrestrial images, colour orthoimages of the vaults, the cathedral's outer southern facade, and the inner western wall. This data represents an objective record of the state of the cathedral at the time of the survey. As such, it is very valuable. In the near future, it can also help the project's scientific board to plan the next phases of the survey more precisely. The vagueness of the first-session specifications should indeed be worked out: just asking for a high-resolution 3D model is not enough anymore. In particular, the resolution of the scan and of the photos should be clearly specified, in some cases depending on the place in the monument, the type of architectural element or the type of material. Image products which were neglected in a first approach might also be reconsidered, as an efficient means of recording the facades of the cathedral more precisely. The ENSG should soon be meeting the project's scientific board to discuss these issues, regarding both acquisition and data processing. If some new technical challenges appear to be interesting for the ENSG, the next PPMD class could work again in Amiens.

6. ACKNOWLEDGEMENTS

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