Integrated 3D Geomatics for Archaeology: Case Study Malta

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Abstract. This article discusses the integrated use of different 3D geomatics techniques: digital aerial photogrammetric restitution, advanced SBAS GNSS and robotized total station measurements. The aim is the realization of both an orthophoto plan and a digital elevation models (DEM) of the whole research area. Quality control, e.g. by applying accuracy analysis of the DEMs, is hereby of vital importance. The integration of these different techniques and the resulting final products are used for an important archaeological campaign on the island of Malta. This successful case study can be representative for many archaeological applications where high quality reference data are required for large areas. Especially when multiple archaeological sites are spread over the landscape, it is essential to have orthophotos or a vector dataset, covering the areas of interest. An orthophoto plan and DEM with an area of ca. 20 km² on the north western part of Malta (Valley of Bidnija and Burmarrad) have been constructed by the authors. Several Punic and Roman sites are located in this area and are documented by researchers of Ghent University in collaboration with the University of Malta and the Superintendence of Cultural Heritage Malta. The project is financed by the Flemish Fund for Scientific Research and entitled “Malta Survey Project 2008 (MSP2008). The orthophoto plan and DEM make it possible to put separate campaigns in a wider spatial context, which enables the detection of possible horizontal relations between the sites. Moreover, combining documented archaeological sites with a DEM enables the analysis of vertical relations. This explains the necessity of elevation data in archaeological research of e.g. water household management on ancient sites. In many cases, no digital elevation models with the desired quality are available. Therefore, the necessary DEM has to be measured and computed for the specific project. The final joined DEM for the whole area of this project is based on 10 photogrammetric stereo couples, with a scale of 1:10 000 and a resolution of 25 cm, and has been georeferenced by GNSS (CNAV). These stereo couples have been processed using the photogrammetric software VirtuoZo. The quality analysis of the DEM, based on overlapping zones between different orthophotos, is executed by the point processing software WinTopo. Different derivative products from the orthophoto plan and DEM - like contour line maps, 3D models, hillshade maps and others - will serve in further analysis of the ancient sites on the island of Malta.

Keywords. Digital photogrammetry, archaeology, GNSS, DEM generation

1. Introduction

The main purpose of this work is to obtain an accurate digital elevation model (DEM) as well as an orthoimage of archaeological sites located in the northern part of the island of Malta (Fig. 1). The generation of these products is the basis for the archaeological inventory of Punic and Roman settlements, and allows to study the position of the sites in the landscape.

Figure 1: Project region (Malta)

Existing DEMs of Malta, with a typical accuracy of ca. 10 m, appeared too coarse for the intended archaeological use. Therefore, different approaches leading to DEM generation were taken into consideration: satellite imagery, aerial photographs, INSAR, extensive terrestrial surveying (GPS, total station,…), etcetera.

The selected approach consisted of acquiring high quality aerial photographs (scale 1:10.000, 25 cm resolution) with a forward overlap of 60%, so that a conventional stereo coverage of the study area was obtained. In 2009, a one week field campaign was organized to acquire a set of 65 reference points in an absolute coordinate system. These points are equally distributed over the study area and acquired using a SBAS-GNSS controller (C-Nav). The reached accuracy of these points is approximately 0.50 m. The restitution, including absolute and relative orientation, was performed using a digital photogrammetric workstation and VirtuoZo software. Combining the precise *x*, *y* and *z* coordinates of at least 6 points with two corresponding stereoscopic images in VirtuoZo, a referenced 3D model, an orthophoto and a contour line map was generated for each separate stereo couple. Finally, a quality assessment on the coherence of the DEM model was performed.

In short, the following 4-steps were executed:

1. Acquiring aerial photographs of the project region;
2. Acquiring ground control points using GNSS;
3. Digital photogrammetric restitution;
4. Quality control.

An overview of these steps will be given in this paper.

2. Acquiring aerial photographs of the project region

Corona KH-4B imagery, that provides a resolution of up to 1.8 m, proved not to be available for our area of interest. Indeed, three-dimensional analysis of Corona imagery has enormous potential for archaeological research [1], and moreover with affordable price and sufficient ground resolution. There are several organizations and companies offering aerial and satellite data of the study area.

One of them is the U.S. Geological Survey. This organization manages a dataset of images declassified in 1996 by the US government, but none of the Corona KH-4B series was available for the region under consideration. Another organization is the National Archives and Records Administration (NARA) with their Defense Intelligence Agency (DIA) files, dated from 1941 and at scale 1:50.000, but also not covering the region of interest.

The Ordnance Survey from United Kingdom, whose colony Malta was before, has no images from the overseas territories anymore in their archives. Some of that imagery could, as they told us, be hosted in the Keele Collection. These are the Aerial Reconnaissance Archives and were before saved by the Keele University, but are now saved by the RCAHMS (Royal Commission of the Ancient and Historical Monuments of Scotland). The RCAHMS has also a collection of imagery, but it was not clear if the study area was covered. Both ways were not further investigated as in the mean time we had information that local agencies on Malta also offer high quality and more recent aerial photographs.

The Malta Environment and Planning Authority (MEPA) offers aerial pictures dated from 2008 at scale 1:10.000. Another company, Aerogrid/Aerodata, sells stereo pairs with the same scale as the last organization and 25cm of ground resolution are offered. Finally, the Maltese private company Datatrack was contacted, which provide quite accurate imagery (stereo pairs with a ground resolution of 25 cm, dated from 2001, and the scale is 1:10.000). They could also deliver camera calibration files in order to work in metric mode.

The data were provided in a digital format, scanned by professional scanners with a resolution of 1000 dpi. The file format of the picture is lossless TIFF. One of the photographs covering the region was only available on paper (model 339, see further). This photograph was scanned by a semi-professional scanner at a lower resolution of 500 dpi and without any correction possible for the camera calibration file.

In total, there are 10 photographs of higher accuracy (1000 dpi with camera calibration file) and other one with lower accuracy (500 dpi with no camera calibration). That means 10 DEM models to be constructed, two of them in non-metric way.

3. Acquiring ground control points using GNSS

After the relative orientation of the stereo couple, the pixel coordinates of the photogrammetric model have to be linked with geographic coordinates. To perform this absolute orientation of the model, anchor points are used [2]. These points, also called GCPs (Ground Control Points) can be acquired by identifying reference points on both the image and a reference map [3]. This creates a mathematical link between the image coordinates of the image itself and the geographic coordinates of the reference map. The method is sufficient when the images have a lower resolution than the reference map, for example to georeference low resolution satellite image. In this paper, the images have a resolution of 25 cm and no maps of the area with such an accuracy are available. Therefore, fieldwork is needed to measure the GCPs with a sufficient accuracy of 0.5 to 2 pixels on the image or up to 50 cm in the terrain [4]. In theory, a minimum of 6 GCPs are required to execute the absolute orientation of the model [5]. It is desirable to measure more points to have ambiguity in the orientation equation and enable the replacement of erroneous points. For each photogrammetric a set of 12 GCPs are selected based on characteristic elements on the images, preferably manmade objects. To reduce the total error of the absolute orientation, GCPs must be distributed equally over the entire area of each stereo couple and clusters or linear distributions must be avoided. The distribution of the selected points and the study area are illustrated in Figure 2.

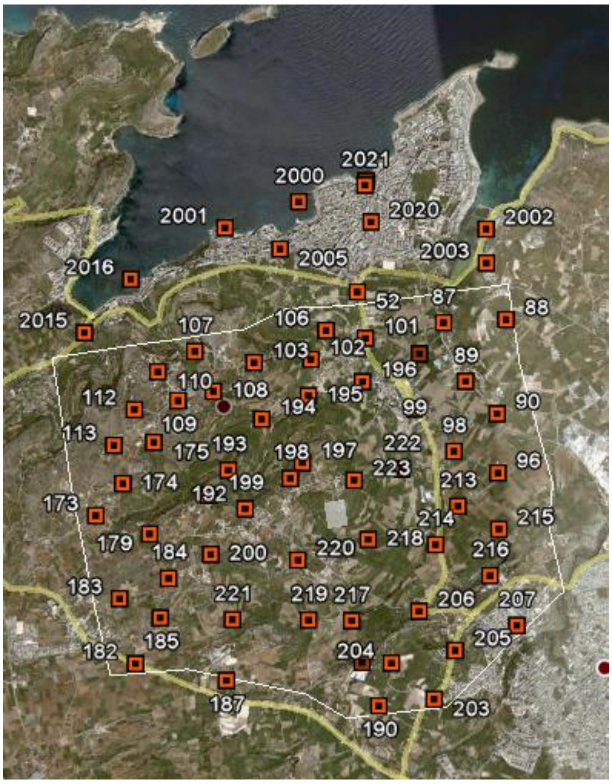

Figure 2: study area and selected GCPs

An abundance of GCPs is not only required to have ambiguities, but is a safety margin as well. Suitable objects on the aerial images may look sufficient, but could be changed in time. In Figure 3, a point is chosen at the end of a hedge or wall, but between the photogrammetric recording and GCP acquisition on the field, a building and a bridge connecting this building and the road has been build. As a result, the true position of the GCP cannot be determined clearly. Even if the image and ground truth seems to match for a given GCP, attention is required for a correct localization.

Figure 3: the bridge on the left image is not on the aerial picture

All GCPs are measured using a C-Nav 2050 GPS module. This is a passive system with a maximal accuracy of less than 10 cm, reached when the InmarSat differential corrections of the StarFire augmentation system are used and an initialization time of 30 minutes is respected. When the reference signal is used, an accuracy of 50 cm can be reached in a few minutes [6]. With respect to the resolution of 25 cm, it will be sufficient to reduce the acquisition time to 5 minutes. The error of the absolute orientation is assessed during the post processing of the images in both VirtuoZo and WinTopo.

4. Digital photogrammetric restitution

For the photogrammetric restitution, both the digital aerial photographs and the coordinates of the ground control points are required . The coordinates of the ground control points are expressed in the UTM 30 coordinate system (Northern hemisphere) (WGS84). The aerial photographs were taken in 2001 with a metric camera with known calibration parameters and later digitized. The images have a photo scale of 1:10 000 and a ground resolution of 0.25 m. The area of interest is covered by ten stereo couples. The images were taken in three flight strips. Two of these stereo couples have a different ground resolution of 0.50 m because they are partially based on an aerial image with a lower resolution of 0.50 m. This aerial image is taken with a non-metric camera.

The digital photogrammetric processing is performed in the VirtuoZo software. In this software package, the stereo couples are structured in two levels: blocks and models. Each block consists of a set of stereo models with the same features and parameters and each model consists of two stereo images which can be photogrammetrically processed. Each of the ten stereo couples is processed to obtain a DEM and a orthorectified image of that part of the area.

In the first step of the photogrammetric restitution, the internal orientation, both images of the stereo couple are corrected based on the camera calibration file. The internal parameters used for the internal orientation are the coordinates of the principal point, the focal length and the coordinates of the fiducial marks. For the stereo couples taken with a metric camera, these fiducial marks are visible on each image (Fig. 4). Based on the fiducial marks, the images can be orientated as they were positioned inside the camera on the time of the recording. For the two stereo couples taken with a non-metric image, the internal orientation cannot be performed, since no camera parameters are available.

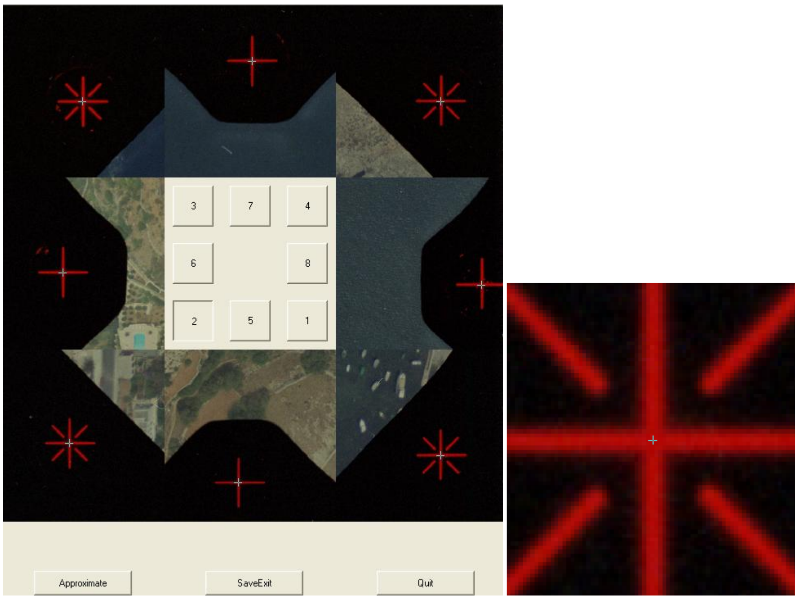

Figure 4: Internal orientation in VirtuoZo (left); Close-up of fiducial mark (right)

The relative orientation of both stereo images is an operator controlled automatic operation. The software automatically searches for homological points on both images of the stereo couple. These results have to be manually revised by the operator to check if the indicated points really represent the same points on the images. At the end of the relative orientation, at least 150 to 200 homological points have to be confirmed for each stereo couple.

The coordinates of the ground control points measured in the field campaign allow to georeference each stereo couple in UTM 30 (North) coordinates. This absolute orientation is based on at least six GCPs per stereo couple. The RMS limits in *x*, *y* and *z* direction for the absolute orientation are set at 0.50 m for the stereo couples with the highest ground resolution (0.25 m). For the two stereo couples with a lower ground resolution (0.50 m), the RMS limits are set at 1 m. Table 1 shows that for each stereo couple, the RMS on the absolute orientation lies within the respective error limits.

The accuracy of the absolute orientation of stereo couple largely depends on the accuracy of the measured ground control points in the field campaign and the accuracy with which these ground control points can be recognized and indicated on the images. On average, twelve ground points per stereo couple were measured and could be used for the absolute orientation. These ground control points are equally spread over the overlapping area of the stereo couple, depending on the accessibility of the terrain and the criterion of unambiguously detection on both the image and the terrain.

Table 1: RMS on the ground control points of each model for the absolute orientation

	RMS X (m)	RMS Y (m)	RMS 2D (m)	RMS Z (m)	RMS 3D (m)
Model 244-243	0.38	0.42	0.57	0.13	0.58
Model 243-241	0.34	0.29	0.45	0.37	0.58
Model 241-239	0.38	0.26	0.46	0.43	0.63
Model 168-170	0.40	0.10	0.41	0.43	0.60
Model 170-172	0.20	0.45	0.49	0.46	0.67
Model 172-174	0.33	0.42	0.53	0.41	0.67
Model 344-342	0.35	0.27	0.44	0.53	0.69
Model 339-338	0.39	0.31	0.50	0.38	0.63
Model 342-340*	0.51	0.65	0.83	0.79	1.14
Model 340-339*	0.44	0.55	0.70	0.79	1.06
* These stereo couples have a lower ground resolution (0.50 m)					

There is no operator interaction possible in the epipolar resampling and the image matching of the stereo couples. Also the elaboration of the digital elevation models and the orthorectified images is automatically performed by the software. The DEMs are generated with a DEM spacing of 0.50 m. The ground sampling distance (GSD) for the orthophotos is set at 0.25 m. For the stereo couples with a ground resolution of the images of 0.50 m, the GSD of the orthophotos is set at 0.50 m. Before the final DEMs and orthophotos are generated, the results can be manually edited to correct large errors. In this project, the largest errors are located in the sea because in these areas the image matching gives poor results, due to the lack of contrast and the lack of recognizable homological points. To edit these errors, the elevation values of the sea are changed to a constant height level. This editing will improve the final results without influencing the geometrical information in the area of interest. VirtuoZo generates a quality report for each stereo couple. Based on this report an analysis of the correctness of each DEM can be performed. For the stereo couples with the ground resolution of 0.25 m it can be concluded that the average error between the *z*-value of the ground control points and their *z*-value in the generated DEM is 1.00 m. The stereo couples with a resolution of 0.50 m have an average DEM error of 2.30 m.

5. Quality control

In order to assess the coherence of the 8 DEM separate models, the height differences in the overlapping zones of the sub models can be analyzed, as no independent test set of ground reference

points was available. This will give an idea of the accuracy of the sub models. The overlapping zones are located at the borders of each sub model: it can be expected that the errors are bigger near the borders than in the center of the sub model The height differences in these areas may be considered as a “worse case” situation.
For the comparison, and to flatten out local spikes in the model, the average cell height in 20 by 20 m DEM cells was computed for each separate model. Next, the cell height difference between two overlapping adjacent sub models was computed (table 2).

Table 2: Analysis of the height differences in overlapping sub models (in %)

model 1	model 2	within 1 m	within 2 m	within 3 m	within 4 m	within 5m	outside 5 m
168-170	170-172	50.0	89.9	96.2	98.5	99.3	0.7
170-172	172-174	62.3	93.9	96.7	98.9	99.1	0.9
239-241	241-243	51.4	70.2	78.5	85.0	89.2	10.8
241-243	243-244	71.5	92.0	95.5	97.3	98.1	1.90
338-339	339-340	28.3	50.6	67.6	78.3	84.1	15.9
339-340	340-342	29.1	54.6	73.1	85.3	94.4	5.6
340-342	342-344	42.4	82.2	96.1	98.5	99.1	0.9
Average of all models		47.9	76.2	86.2	91.7	94.8	5.2

Based on Table 2, it becomes clear that in global 47.9 % of the cases, the cells have a height difference of less than 1 m, 86.2 % less than 3 m and 94.8 % less than 5 m in the overlapping regions. The results of the less accurate 340-339 model (due to the lower accuracy aerial photograph 339) are the main raison for this somewhat higher than expected value. Without model 339, 55.5 % of the cells have a height difference of less than 1 m, 92.6 % less than 3 m and 97.0 % less than 5 m in the overlapping regions.

Is there a systematic difference in height between sub models or is the variance of heights within the sub models the origin of the height differences found? In table 3, the average height difference between the sub models is computed. The algebraic average height difference of all separate models is 28 cm, but individual sub models show differences of up to 1.82 m. Again, without the less accurate 339 model, the maximum value of the average height difference between sub models is 71 cm.

Table 3: Analysis of the average height differences between overlapping sub models

	Surface (m²)	# pts	Average (m)	StDev (m)
168-170 versus 170-172	292000	730	0.00	2.23
170-172 versus 172-174	183200	458	0.71	2.10
239-241 versus 241-243	87200	218	0.71	2.84
241-243 versus 243-244	640400	1601	-0.15	1.38
338-339 versus 339-340	2819600	7049	-0.79	4.00
339-340 versus 340-342	1402400	3506	-1.82	2.00
340-342 versus 342-344	309200	773	-0.63	2.46
Average			**-0.28**	**3.22**

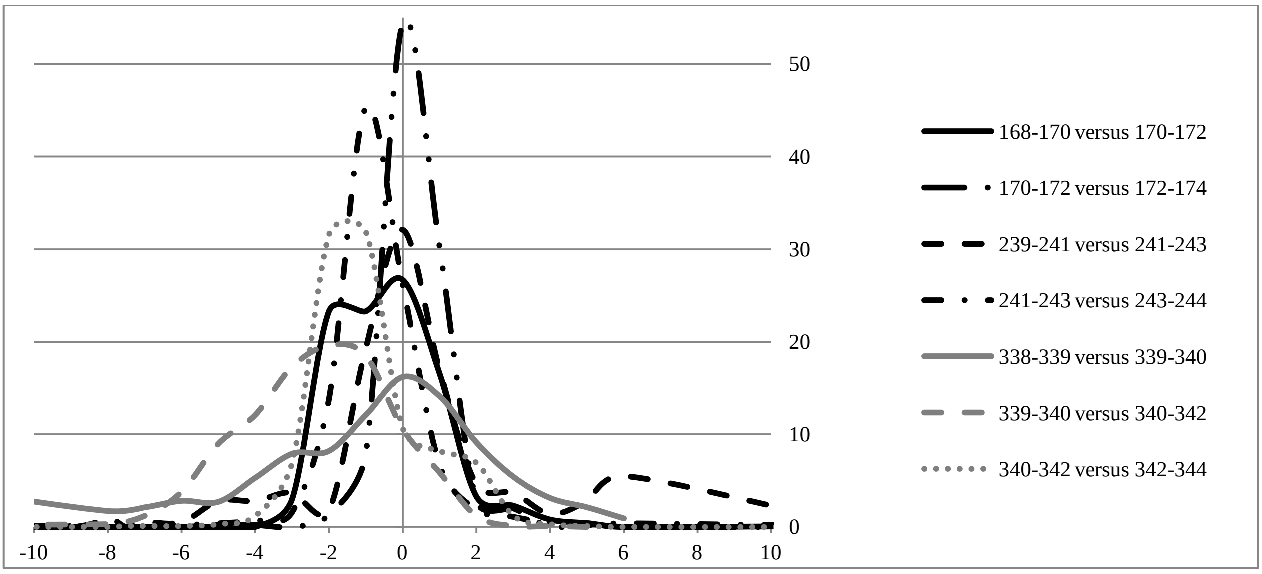

Figure 5: Height differences in overlapping zones of the sub models

As a conclusion, the height coherence of the model can be considered to be in general better than 1 m in overlapping areas. In the final model in overlapping zones the average cell height of the 2 sub models was computed, further reducing the height differences. In the center, the height accuracy can be assumed to be better than at the borders or overlapping areas and thus significantly less than 1 m. As the accuracy of the GNSS ground control points, used to build the DEM models was of the order of 0,5 m, the height quality of the final DEM model can be considered to be consistent with the expectations and therefore sufficient for archaeological use.

6. Conclusions

In this paper a methodology for the generation of a DEM has been discussed, based on digital aerial photographs on scale 1/10.000. For this generation, a field campaign of 65 GCP measured by GNSS was performed to allow the restitution of 10 stereoscopic models with an accuracy of less than 2 pixels or 50 cm. The quality was assessed by an analysis of overlapping zones where a mean algebraic difference of 28 cm was computed. These accuracies meet the geometric requirements needed for the archeological prospection.

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