

UNDERWATER PHOTOGRAMMETRY DIGITAL SURFACE MODEL (DSM) OF THE SUBMERGED SITE OF THE ANCIENT LIGHTHOUSE NEAR QAITBAY FORT IN ALEXANDRIA, EGYPT

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ABSTRACT:

Underwater photogrammetry in archaeology in Egypt is a completely new experience applied for the first time on the submerged archaeological site of the lighthouse of Alexandria situated on the eastern extremity of the ancient island of Pharos at the foot of Qaitbay Fort at a depth of 2 to 9 metres. In 2009/2010, the CEALex launched a 3D photogrammetry data-gathering programme for the virtual reassembly of broken artefacts. In 2013 and the beginning of 2014, with the support of the Honor Frost Foundation, methods were developed and refined to acquire manual photographic data of the entire underwater site of Qaitbay using a DSLR camera, simple and low cost materials to obtain a digital surface model (DSM) of the submerged site of the lighthouse, and also to create 3D models of the objects themselves, such as statues, bases of statues and architectural elements. In this paper we present the methodology used for underwater data acquisition, data processing and modelling in order to generate a DSM of the submerged site of Alexandria's ancient lighthouse. Until 2016, only about 7200 m² of the submerged site, which exceeds more than 13000 m², was covered. One of our main objectives in this project is to georeference the site since this would allow for a very precise 3D model and for correcting the orientation of the site as regards the real-world space.

1. INTRODUCTION

In 1994, the Centre d'Etudes Alexandrines (CEALex, USR 3134, CNRS) launched the first scientific excavation in the field of underwater archaeology in Egypt on the submerged site of the lighthouse of Alexandria situated on the eastern extremity of the ancient island of Pharos at the foot of Qaitbay Fort, which was constructed at the end of 15th century by the Mamluke Sultan Qaitbay. The submerged site was discovered in 1960 thanks to the pioneering work of Kamel Abou Elsaadat, and in 1968 Honor Frost undertook a UNESCO mission on the site which led to the publication of a preliminary report revealing the importance of the site (Empereur, 2000) The underwater site of Qaitbay Fort holds the ruins of the lighthouse of Alexandria, a legendary monument that stood for almost 17 centuries. It was built towards the beginning of the 3rd century BC and was accessible until the end of the 14th century. The last mention of the visible presence of its ruins dates to 1420, almost 60 years before the construction of Qaitbay Fort. (Hairy, 2007).

2. EXCAVATIONS AND DOCUMENTATION CONTEXT

Underwater excavations began in 1994 under the direction of Dr Jean Yves Empereur, director of CEALex, in the hope of shedding new light on the question of the image of the lighthouse. These excavations led to the reconstitution of certain parts of the lighthouse and to an understanding of the design process. Nevertheless, the study of the site ran up

against the limitations of traditional data recording methods. The extent and unique nature of this sunken site have encouraged innovation in data gathering, both as regards the ancient material — more than 3525 blocks — (fig. 1) and the overall site itself, whose size and uneven contours make any analysis complicated. (Hairy, 2009).

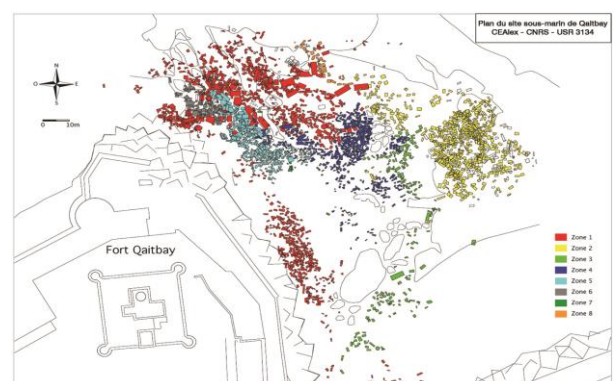


Figure 1. Map of the underwater archaeological site of Qaitbay (CEALex)

In 2009/2010, a 3D photogrammetry data-gathering programme was launched, particularly focusing on the broken statues that surrounded the lighthouse (Hairy, 2011). The research and development department of EDF had begun this work in 1998 and it was continued between 2009 and 2012 as part of the

ANR-SeARCH programme. In 2012-2013 the aim of the campaigns was to continue the virtual reconstitution work on the pair of colossal royal statues that once stood next to the lighthouse. This work demonstrated that photogrammetry was the new solution for rapidly providing quality "digital duplicates" on the scale of the elements, whether sunken or lifted (Reuter, Mellado, Granier, Hairy, Vergnieux, Couture, 2011). With around 30 blocks removed from the sea and more than 3000 pieces still underwater, some of which weighing almost 40 tons, this was an important step forward. From 2013, with the support of the Honor Frost Foundation (HFF), the gathering and processing of photographic data in this research were improved and led to a clear development in data gathering techniques and the consequent improvement in the quality of results (Abd Elaziz, Elsayed, Hairy, Soubias, 2016). Fully manual photographic data acquisition methods were applied, using a DSLR camera and low cost materials to develop a digital surface model (DSM) of the entirety of Qaitbay underwater site, which exceeds more than 13000 m². One of the objectives of this project is to use photogrammetry to create a digital duplicate of the submerged site.

3. METHODS AND TECHNIQUES OF DATA ACQUISITION

Archaeological excavations are often destructive, and so it is important to have detailed documentation reflecting the accumulated knowledge of the excavation site. This documentation is usually iconographic and textual. Graphic representations of archaeological sites such as drawings, sketches, watercolours, photographs, maps, and photogrammetry are indispensable for such documentation (Drap, 2012). The underwater site of the lighthouse of Alexandria lies in the open sea to the east of Qaitbay Fort. It is affected by natural forces, waves and currents, and by sewage discharge, which changes the water quality. In addition, the prevailing wind is N-NW, which is variable from December to May (El-Gindy, 2000 p. 144). The poor sea conditions and poor visibility, rarely exceeding 3 m because of the suspensions and sewage, obliged us to acquire a wide experience in site documentation by photogrammetry.

3.1 Equipment and Materials

Any underwater archaeological surveying technique must satisfy two contrasting requirements: speed and accuracy. Although many different photogrammetry techniques have been used on underwater archaeological sites around the Mediterranean, it is often difficult to select one that will be suitable for a particular site (Green, Baker, Richard, 1971). In our case the underwater archaeological site of Qaitbay is particular, not only because of the abovementioned sea and weather conditions, but also for its uneven rocky bottom and the variation of the depth between 2m to 9m. The use of heavy materials such as metal photo-towers or frames installed upon the site was impossible; even more modern equipment such as side-scan sonar/AUV and ROV were unsuitable due to the rocky bottom and shallow waters in some areas of the coast. Thus, other methods and techniques of data acquisition were adapted according to the weather conditions and topography of the site. Our technique for preparing the site for photography and cartography was completely manual using simple and

cheap materials such as linear scale bars, iron rods, measuring tapes, lines, buoys, numbered tags, and a compass (fig.2).



Figure 2. Materials used in data acquisition (photo by Mohamed Elsayed)

3.2. Data acquisition

In the spring of 2014 a CEAlex team of ten people prepared the site for data gathering. First of all, an area of 450m² (30m x 15m) located about 10 metres north-east from the breakwater (fig. 3) at a depth of between 3m to 5m was chosen to be the base of the photographic plan of the entirety of the submerged site. For practical reasons, it was divided in two smaller zones, A and B (fig.3). Later on we developed the different sectors of the site in the capture plan around it. This zone, known as Zone 1, held some of the more remarkable features of the archaeological site; parts of the monumental door of the lighthouse, bases of statues and other architectural elements. This zone was considered as a difficult part of the site because of the variation in bottom levels and the volume of the archaeological elements: e.g. a statue base 2 m high, 2.60 m long, weighing about 40 tons; a door lintel 2 m high, 5 m long, weighing about 43 tons.

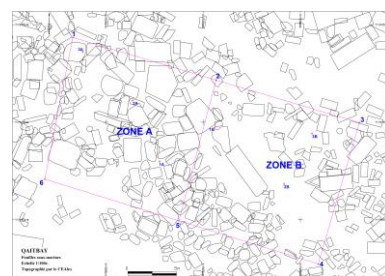


Figure 3. Zone 1, initial sector of data acquisition (CEAlex)

Zones A and B were partitioned into 2 m wide lanes running transversally over an area of 15 m by 30 m, marked out by ropes attached to iron rods (fig.4). At the beginning the lanes served to guide the photographer, to give him points of reference, to fix his movement in a straight line and to control the overlapping of the photographed area. This technique makes it possible to work in any weather conditions and especially when the visibility is poor, but it has the disadvantage of an extremely long preparation time, since it takes about ten days to set up an area of 450 m². This constraint encouraged the development of a process that would save time and be less expensive by reducing the quantity of material

required for preparation and be less polluting by limiting the loss of material: the rods and lines were difficult to recover once installed. During the first season of 2014, about 750m² were covered (fig.5). In order to accelerate the work in the following seasons (autumn 2014, then 2015 and 2016) we avoided the long preparation time by using only measuring tapes to delineate the work zone and linear scales in the area of photography.



Figure 4. Preparing the first part of the site in 2014 (photo by Ashraf Hussein)

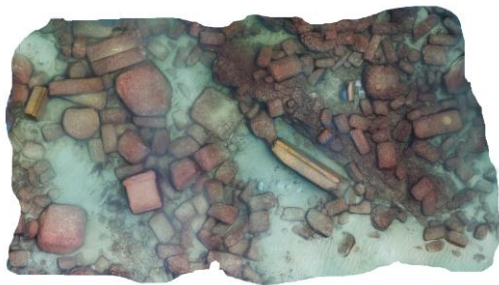


Figure 5. Spring of 2014, first orthophoto of 750 m² composed of 1322 images (photography by Mohamed Elsayed, data processing by Mohamed Abdelaziz)

3.3 Photography

The first step towards creating an accurate three-dimensional model of the site is to take a series of good photos using a good camera. The most important thing for the precision and the accuracy of the work when using manual methods is the diver's competence in, firstly orientating underwater and secondly in respecting the level of the flight plan, which must not exceed 3 m height above the site. The data capture method is generally inspired by the classic approach used in the aerial domain. The flight plan and photographic work for obtaining the DSM was undertaken by Mohamed Elsayed using a DSLR camera (Nikon D700 fixed 24mm lens) in a hemispheric dome housing, which allows for a wide coverage area and close proximity to the subject especially in low visibility. All the captures were taken in a manual mode without flash whatever the sea conditions: f/stop and shutter speed varied according to underwater visibility and luminosity, sometimes using $f/7.6$ with $1/60$, or less, $f/5.6$ and $1/40$, depending on the condition of the water itself. From 2014 until 2016, about 26 weeks were dedicated to the photographic survey, and eventually 50152 photos (fig. 16) were used to create an automated orthophoto representing a part of DSM covering an area of 7200 m² of the 13,000 m² of the site (fig.15). The flight plan method developed for the Qaitbay site required a period of experimentation to manage the

constraints of the underwater context, including the troublesome problems of visibility on the site connected to turbidity, suspended particles and sewage. Further difficulty was occasioned by the large surface area (1.3 ha) and the size of certain blocks, requiring the combining of several methods of shooting.



Figure 6. Underwater photogrammetry data acquisition (photography by Philippe Soubias, processing by Mohamed Abdelaziz)

For these reasons, it has been impossible to gather data in order to process the entire site at one time. The data capture method has been adapted to respond to these constraints, and so several methods were applied during the missions of 2014, 2015 and 2016. In order to increase the area covered by photography in previous missions we reduced the materials used in the operation to save preparation time of each zone. The flight plans of the initial experiences in 2014 served as the basis of future work, the diver moving along lines attached to a rod, doubling back and forth after 20 m of continuous shooting to capture the surface model. At the end of the lane, the photographer should turn around and cover another side while respecting the overlap (fig.7). The diver maintains his path by visual orientation, checking his trajectory against the features of the seabed, the many ancient blocks, the uneven surface (fig.6) and scales placed on the bottom. Measuring tapes and buoys mark the boundaries of the area to be covered during the flight plan.

The major difficulty encountered in the landscape of the underwater site lies in the significant variation in the altitudes of the seabed. In some areas, there is a shift from -8 m to -4 m moving northwards, and from -9 m to -5 m while following a south-east direction. The photos taken during these flight plans, were always close to an angle of 45° and not from vertically above (Fig.7), thus capturing the rugged reliefs of the site surface. The diver must move in as straight a line as possible and at a constant speed in order to ensure sharp images, and must not exceed a height of 3 m from the bottom or sometimes 1.65 m in conditions of bad visibility. The flight plans require a forward overlap of 70% to 80% and lateral or side overlap of the same order, which is superior to conventional aerial photography (fig. 16). This overlap rate reduces mistaken pairing by increasing the number of combined photos when matching images within the software. The shots were taken in

different weather conditions: small or large swell, sunny or sometimes overcast weather, but always with sufficient brightness. In 2015 and 2016, the area covered was approximately 7200 m² (Fig. 15).



Figure 7. Methods of capture of the surface model (processing by Mohamed Abdelaziz)

4. DATA PROCESSING

4.1. Data preprocessing

At the beginning of the project in 2014 the available computer for data processing had limited capability: RAM - 16G/GPU - GT630, 2G/CPU – Intel core i3. This was not practical for such a project but was managed by Mohamed Abdelaziz to achieve good results. The final aim of photo processing with photogrammetry software is to build an ortho-image and a textured 3D model. The first step is the preprocessing of the images, which were dominated by blue/green and yellow colour because of the turbidity of the water, low visibility and lack of light that changes the colour of the images. These photos cannot be used efficiently without prior enhancement, thus image processing is necessary for colour correction, contrast, removing shadows and reducing highlights in order to get more matching points between pairs of images (Fig.9). For this we used Adobe Lightroom and Photoshop for editing photos in such an environment (Fig. 8) and for batch processing. All photos were captured in a RAW format and then converted into JPG to be accepted by the photogrammetry software.

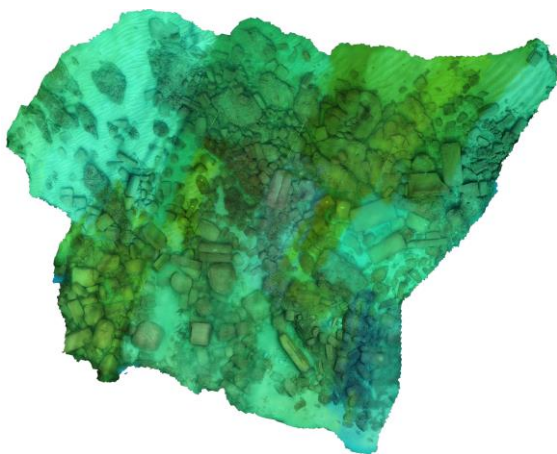


Figure 8. Orthophoto before preprocessing of the raw images showing the different visibility conditions of 2014

(photography by Mohamed Elsayed, processing by Mohamed Abdelaziz)

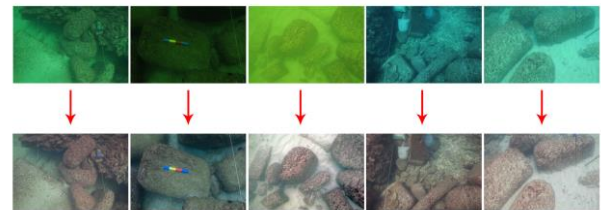


Figure 9. Above, raw images: below, photos edited using LR and PS. From the left to right: green, dark green, greenish yellow, blue, light blue (Mohamed Abd Alaziz)

4.2. The software Metashape (formerly Photoscan)

Metashape is a 3D software application developed by the Russian company Agisoft LLC (Agisoft manual 2019). It generates an accurate 3D model from images, which are converted into a textured 3D model in four straight forward processing steps, namely: 1) Align Photos, 2) Build Dense Cloud, 3) Build Mesh, 4) Build Texture. (Van Damme 2015) (Yamafune, Torres, Castro, 2016). In order to improve the results some actions in the software were added, such as picture masking, deleting erroneous points. Beginning by feeding uncalibrated overlapping images into the software, the camera auto-calibration runs automatically through mathematical algorithms; the software detects and then tracks how many points move throughout the series of images. Even the images that are not calibrated will be automatically computed inside the photogrammetry software. (Beltrame, 2015).

4.3. Building a dense point cloud and mesh with low computer capability

Metashape uses a so-called “feature detection algorithm” to automatically identify and match features in overlapping pictures. The software automatically aligns the pictures relevant to one another based on the detected features and the camera calibration parameters (Van Damme, 2015). The next step is to build a dense point cloud, respecting the low capabilities of the actual computer, avoiding ultra-high resolution and medium subsetting because once started we found that it took about two weeks of processing, and then the software could crash after hours of processing. To resolve this problem, Metashape produces a python script called “split in chunks” (http://wiki.agisoft.com/wiki/Split_in_chunks.py), which we used. Since we must process huge numbers of photos, it was impossible to treat all of them at one time, so a dense cloud and then a mesh can generate smaller boundary boxes, which is a box containing the aligned photos, which the software can then merged back again into a single chunk. Then, by reducing the size of the box, the software will process what is inside using a low amount of RAM/GPU/CPU. Ultimately, processing a dense point cloud in a low setting can produce a satisfactory result through strict adherence to the flight plan and the quality of the photos: we can see the details on the model (fig.10). Processing the data from the 2014 mission took more than 30 hours to create a dense point cloud with total points of more than 150 million.

The next step is to build a mesh (the geometry of the created model based on a point cloud). The final step in the process is to generate a texture map, which is projected from the camera positions onto the 3D model itself.



Figure 10. Above, resized boundary box using “split in chunks” script; below, the dense point cloud (150 million points) processed in low setting quality (Mohamed Abdelaziz)

4.4. Workflow

Between 2014 and 2016 a massive number of photos, about 50152 (fig.15), were used to generate the final 3D model/orthophoto covering 7200 m² of the submerged site of Qaitbay. Thousands of images were processed during every mission using a unique processing method in Metashape, because the characteristics of the PC used in processing, as mentioned above, could not handle all of these photos. The best solution was to process the photos day by day to have a chunk for each day, so we have in total 39 parts of the site representing the different daily captures on the underwater site during the different campaigns from 2014 until 2016. Between each chunk there is an overlap of 25% which helps to merge the processed areas into each other on Metashape by using manually-positioned digital marker features on each of the paired chunks, then the others are referenced to the base, so the second chunk will merge to the base and the third will merge to the second and so on (fig.11).

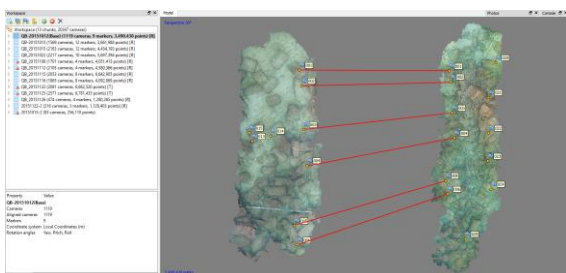


Figure 11. Markers for merging chunks (Mohamed Abdelaziz)

4.5. Georeferencing

Georeferencing of the DSM is an ongoing task that was begun during the last campaign of 2016. Small rubber numbered tags and iron rods were fixed onto the flat surface of bedrock to serve as and locate ground control points (GCPs). These were distributed around the whole area that was surveyed during the years 2014 and 2015: more than 30 points were fixed in the different zones. As part of a direct survey method using a total station, the points were indicated on the surface by a floating buoy (fig.12) attached to a rope anchored to the bottom by 20 kg weight to hold it stable when plotting.

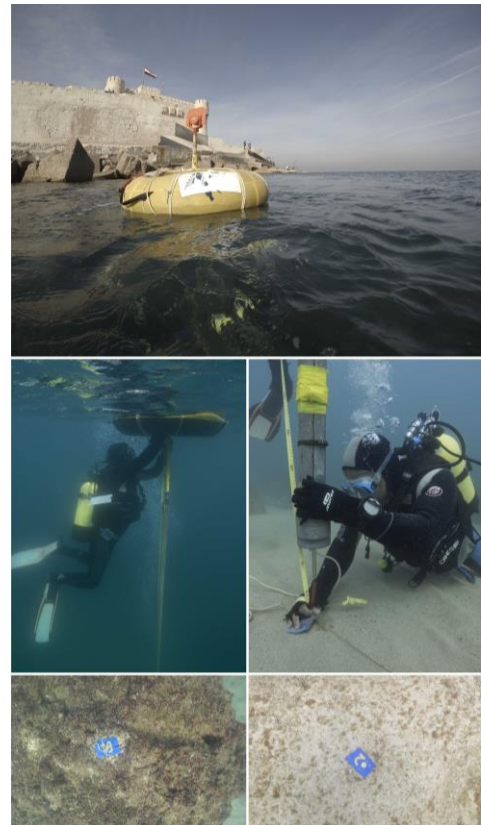


Figure 12. Georeferencing of the DSM (photography by Philippe Soubias and Mohamed Elsayed)

Photographs of these points were captured to mark the position of the GCPs *in situ* with an all-around overlap giving more features to the photos in order to merge and integrate the points into the model created in 2014 and 2015. Since that time, however, the surface of some objects underwater has changed because of concretions and the variation of sand level in some areas of the site. Thus the software did not immediately recognise previously recorded features and the authors were required to introduce further data allowing the software to recognise the underwater blocks which would allow it thereafter to merge the chunks. It was necessary to work each season individually due to the computer limitations. Each season was georeferenced in real world space and was exported into other software, such as Meshlab and Autocad, to obtain the entire 3D model ortho-DEM. In the end, all the output concludes that the mean error resulting from this process is 13 cm. (Fig.13)

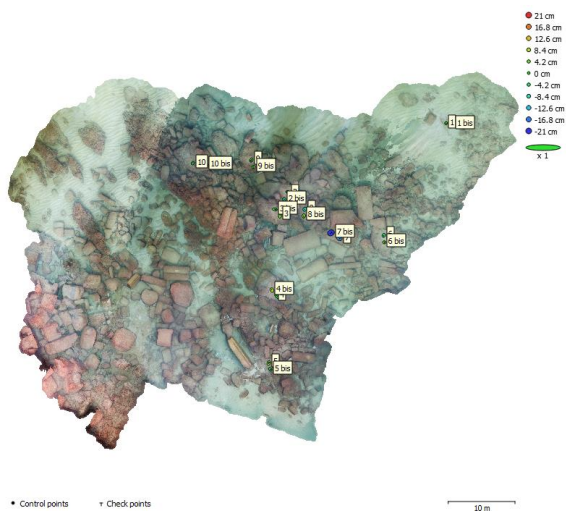


Figure 13. Integrated GCPs in 2016 for the two seasons 2014 and 2015 (Mohamed Abdelaziz)

4.6. Orthophotos and digital elevation model (DEM)

After creating the mesh we can produce the orthophoto and digital elevation model (DEM) in real world space. Sometimes there are some blurry areas in the orthophoto generated by the multiple photos concentrated in one area. Metashape has an option to perform orthomosaic seam line editing for automatically better visual results (Agisoft LLC v. 1.5, 2018). Orthophotos and DEM can be obtained with Metashape in any projection required (Yamafune, Torres, Castro, 2016) though in reality (Zhukovsky, 2013) and we extracted a plan (fig.14), sections, volumes and elevation, however, we found that this takes a very long time and is impractical in an underwater environment. The orthophoto, which is assembled from raw images, produces an average pixel size varying between 0.64 mm and 0.50 mm/pixel because of the height variation of the camera and the surface of the seabed (fig.15). We created the DEM from the mesh rather than the dense point cloud (fig.17).

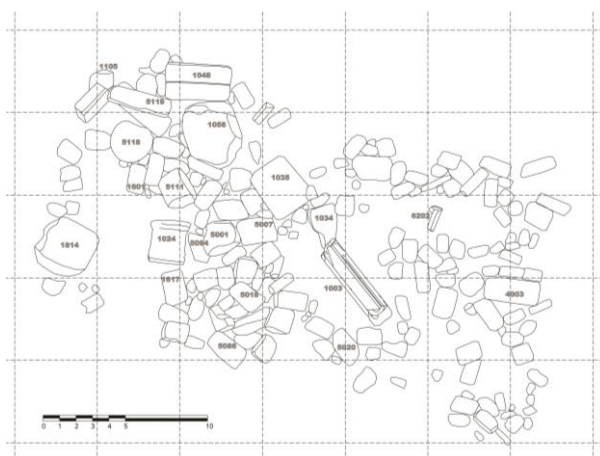


Figure 14. 2D drawing from the orthophoto of 750 m² (Mohamed Abdelaziz)

5. CONCLUSION

One of remarkable things on this site has been the change in sand level between the years 2014 and 2016. This has resulted in the covering of dozens of blocks, which appeared on earlier orthophotos and models only to disappear later on. Fortunately photogrammetry allows us to follow these changes in the site (fig.19). The DSM of the submerged site of the lighthouse near Qaitbay is not yet completed, however our initial experience in underwater photogrammetry to create such a DSM has provided good and efficient results using the technical application of low cost materials for data acquisition and data processing for the documentation of what is a huge submerged archaeological site. More than 7200 m² has been documented, representing about 60% of the total surface area of the submerged site. Nonetheless, we still need improvement in our work in the coming seasons in areas such as:

- Improved georeferencing of the model. We shall increase the number of GCPs in zones captured in 2015 and 2016, and we will position GCPs in future zones before photographing, in order to increase the accuracy of the model. The DSM, once completed, will offer the possibility of performing lengthwise and transverse profiles, and of creating a digital terrain model (DTM) of the site with complementary data. It already allows for the production of orthophoto plans with a pixel size adapted to the power of our computers, which can, in absolute terms, reach a pixel resolution equalling between 0.64mm to 0.50mm on the seabed (fig.15).
- A manual calibration will be undertaken during the next campaigns to compare between the manual and automatic calibration inside the software in order to increase the accuracy of the model itself.
- We can create a DEM from which we can obtain 'z' points or the elevation for any block in the site without using a GPS because the site is already georeferenced. In addition, we can also extract a section to see the uneven surface levels, and the volume of any block in the model (fig.17).
- Having a 2D drawing from the orthophoto on AutoCAD can be a faster means of drafting a plan (within a few days) instead of spending a long time on the submerged site.
- In Meshlab we can apply an ambient occlusion render to the 3D model thus improving visualisation, which can help in counting the archaeological objects (fig.18).
- Since the Qaitbay site is not accessible for people who do not dive, and underwater conditions and visibility are not stable, we could create a virtual diving tour from the model of the area of 7200m² which could be developed in the future, after finishing the model, into a complete video animation of the 3D model.

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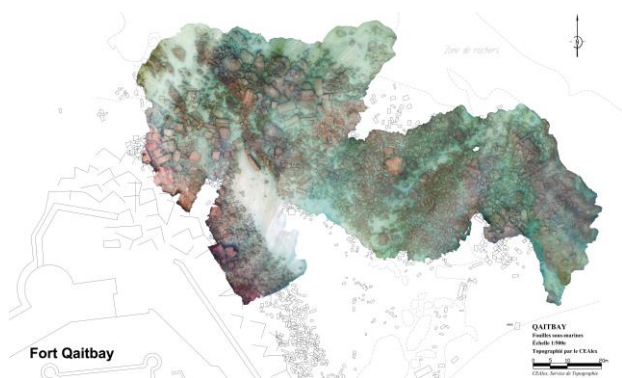


Figure 15. Orthophoto (50152 images) of 7200 m² from 2014 until 2016 (photography by Mohamed Elsayed, processing by Mohamed Abdelaziz)

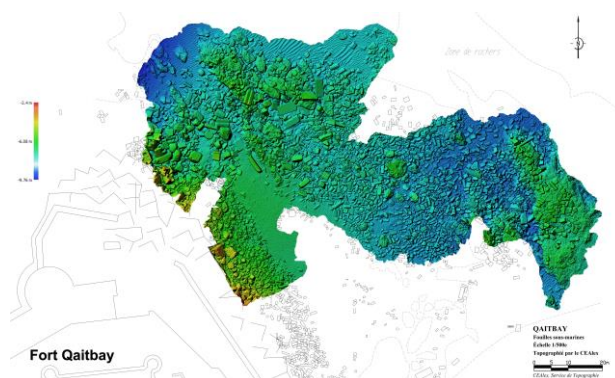


Figure 17: DEM of 7200 m² from 2014 until 2016 (Mohamed Abdelaziz)

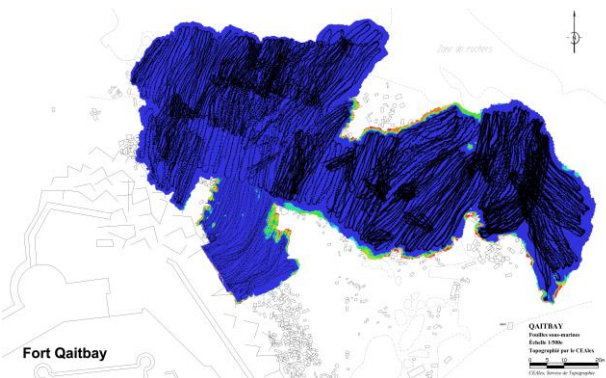
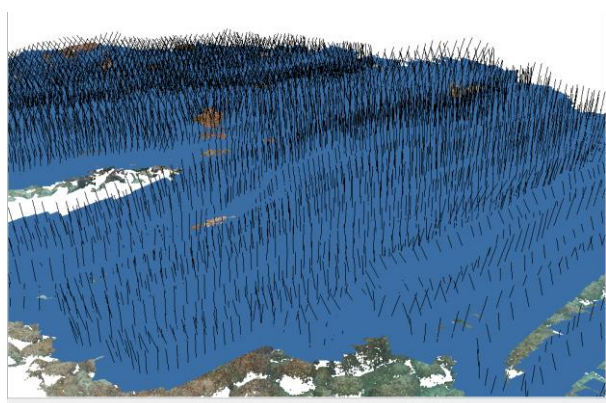


Figure 16. Above, a part of camera positions of small area of the site; below, Camera positions of 7200 m² (50152 images) from 2014 until 2016 (Mohamed Abdelaziz)

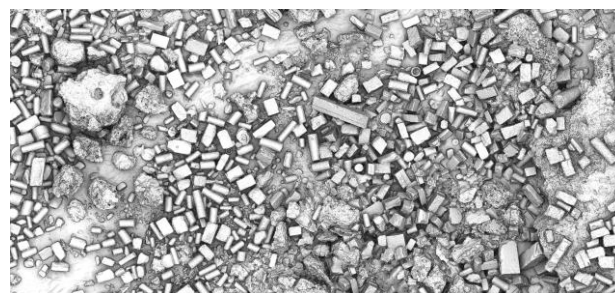


Figure 18. Part of the site showing ambient occlusion render in Meshlab (Mohamed Abdelaziz)

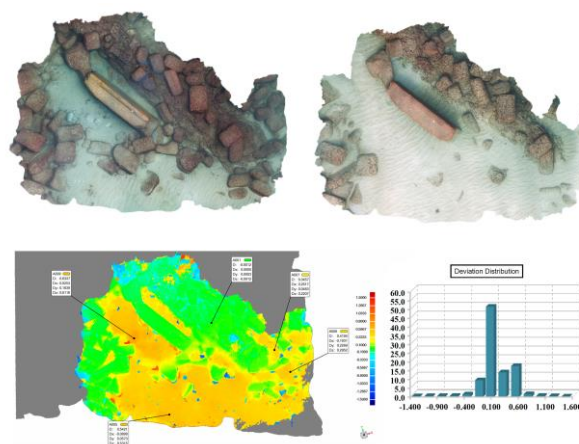


Figure 19. Above, from left to right an orthophoto (season 2014 and 2016) showing the different level of sand; below, Inspection Overlapping Area 2014-2016.

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