Alexander Gatzsche

# Case study of an open source application for 3D acquisition of archaeological structures at the archaeological site Wad Ben Naga[1]

## Introduction

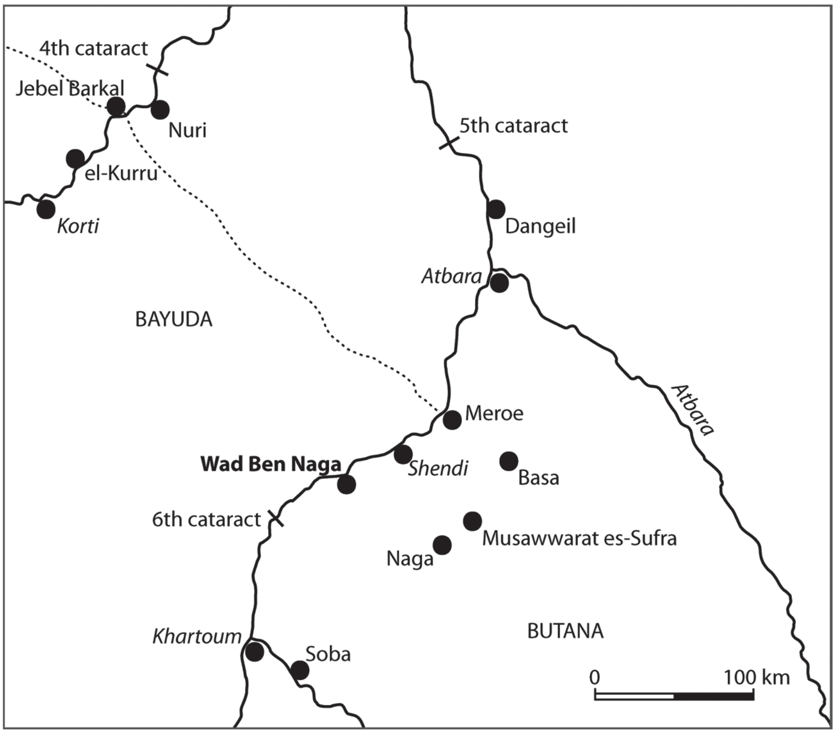



Fig. 1: Map of the Republic of the Sudan / Map of the Island of Meroe.

In 2009, the National Museum of the Czech Republic launched its archaeological activities at the Meroitic site of Wad Ben Naga, located some 130 kilometers north of Khartoum (Fig. 1). So far, the National Museum's Archaeological Expedition to Wad Ben Naga has completed six excavation seasons. The first three seasons[2] were focused on a general survey of the site and re-excavation of structures unearthed by the expedition of the Sudanese Antiquities Services headed by Said Thabit Hassan Thabit between 1958 and 1960.[3] By the third season (Autumn 2011), the Expedition started exploration of the so-called Typhonium (WBN 200), a temple complex remains of which are known from the accounts of early European and American travelers who visited the Middle Nile Region between 1821 and the mid 1880s. This period marks the time from the military campaign the Egyptian viceroy Muhammad Ali sent to the present-day Sudan to the outbreak of the Mahdist revolution. The exploration of the temple complex still remains the main focus of the Expedition's archaeological activities at the site. (Fig. 2)[4]

## 3D computing techniques employed at Wad Ben Naga

Inspired by projects carried out within the framework of conservation and documentation at the neighboring sites of Naga[5] and Musawwarat es-Sufra[6], the Expedition decided to employ 3D scanning technologies for the recording of (1) isolated finds and (2) closed finds in situ. Several finds had already been scanned in this manner during the Expedition's first season by Samuel Rihák).

(1) For the 3D documentation of finds, i.e. ancient artifacts, the Expedition has been using a self-made structured-light scanner which proved to be highly

1 The article was written within the framework of the project "Exploration of the Meroitic Royal City at Wad Ben Naga (Sudan)", supported by the Czech Science Foundation (grant no. 13-09594S).
I want to thank the project director Pavel Onderka for his motivation and invaluable assistance in writing this article.

2 For the preliminary reports cf. Onderka – Dufková 2011, Onderka 2011 and Onderka 2012.

3 Cf. Vercoutter 1962.

4 Cf. Onderka 2012, Onderka 2013.

5 Bauer / Hamann 2011.

6 Kleinitz / Bauer / Näser 2009; Kleinitz / Rüther / Näser 2010.

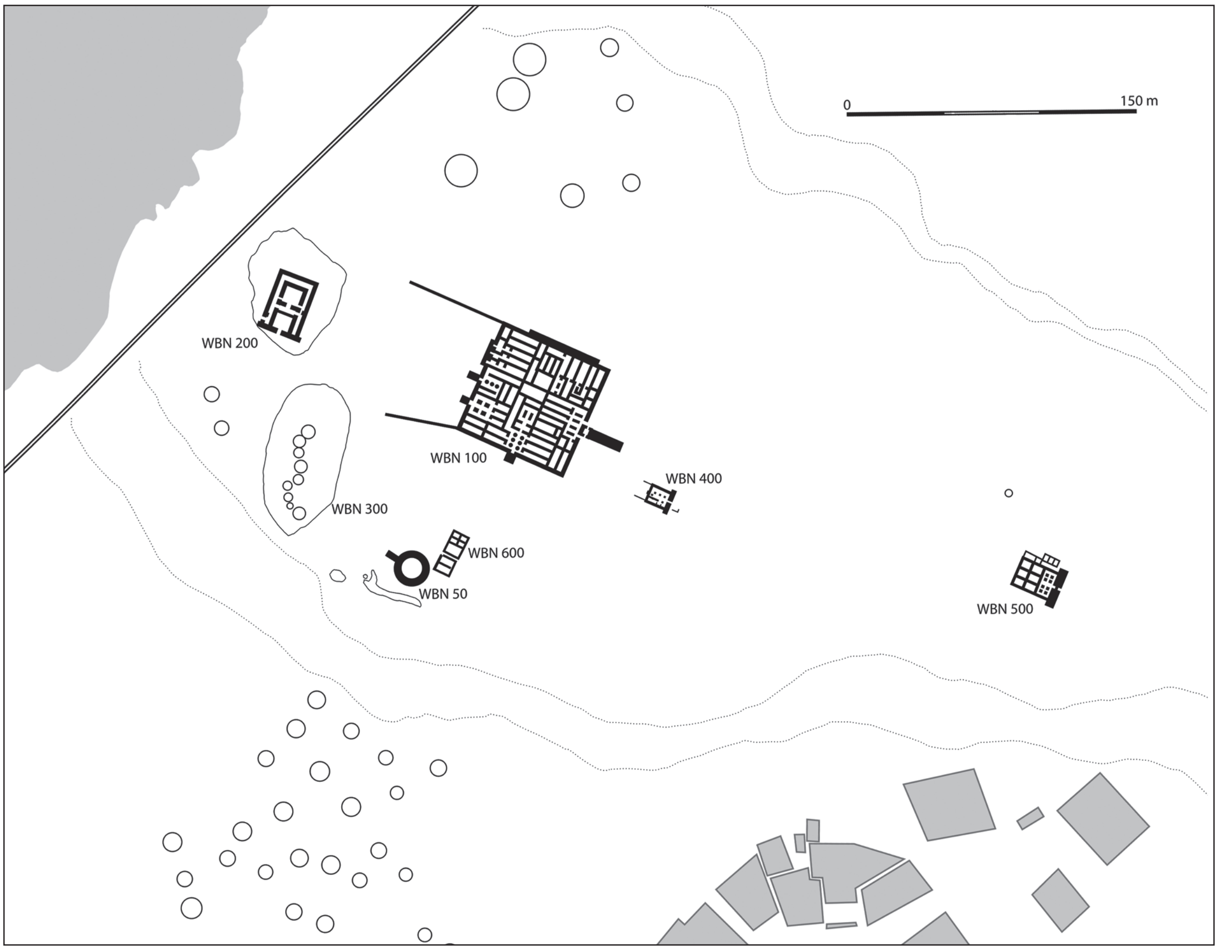



Fig. 2: Plan of Central Wad Ben Naga (after The Archaeological Map of the Sudan).

efficient in producing virtual copies of the objects, allowing further scientific research to be carried out in the premises of home institutions (Fig. 3).

(2) The second method is generally termed as Structure from Motion and is used to document terrain, excavated structures and other archaeological situations.

Fig. 3: Three-dimension scan of a lion head-shaped gargoyle (author).

Within the fifth excavation season,[7] both methods and their incorporation into the routine excavation process were tested. Encouraged by satisfactory results and their compatibility with the established excavation process, these methods were fully employed during the sixth season (spring 2013).[8] The methods proved to be contributive not only towards the ongoing excavations, but perhaps more importantly for the documentation of monuments that were unearthed more than a half century ago and have not received any conservation treatment since.

The possibility of upgrading the documentation and conservation processes with three-dimension technologies was met through innovative application of mainly low-cost and generally available equipment.

7 Onderka / Vrtal / Dašková / Vacek / Gatzsche 2013.

8 Onderka / Vrtal / Gatzsche, *in print.*

## Potential benefits and challenges of the Structure from Motion technique

One of the most important reasons for such a method to be employed is its ability to collect a substantial amount of information during a relatively short period of time (usually limited by the length of individual excavation seasons). Another reason is the possibility to visualize entire structures in all dimensions, or within a single image, in their state of preservation shortly after the excavations are completed.

This is especially important because of the character of the buildings at Wad Ben Naga. Stone was employed only scarcely in the construction of both profane and sacred structures at Wad Ben Naga, as quarries for stone that possessed the required qualities were located a good distance (25 to 30 kilometers) from the site.[9] Thus, even if we disregard extreme weather and climatic conditions in the Sudan, the preservation and conservation of brick structures is difficult and poses special demands on both conservators and archaeologists.[10] The current excavations are located in the proximity of a small wadi that empties seasonal rain water from the archaeological site's surrounding areas. The unearthed walls thus begin to decay immediately after their excavation. Protective backfilling of trenches is a standard procedure before the end of every season (or even earlier than that). However, this prevents the study of all parts of a structure in its full context and complexity.

Irrespective of how accurate and detailed the traditional documentation may be, the excavator is never able to consult the initial archaeological situation again. The absence of this possibility in the real world may, however, be rectified by virtual reality.

The given method targets the possibility of virtual completion of the structures as documented in the moments of the particular excavation. Ideally, the scanning should be carried out during these moments. The position of the sun in its daily cycle, temperature, weather conditions etc., play important roles in the calibration and the process of scanning.

The conditions prevailing in the Sudan thus precluded the use of laser scanners, as a case study from Musawwarat es Sufra has shown.[11] Another disadvantage of this scanner type is its high cost – operation, maintenance, and repair usually require a specialist. In addition, site logistics may preclude use of this type of equipment due to its size and weight.

After considering the requirements of the mission in combination with the above-mentioned factors, the decision was made to employ a 3D surface reconstruction using the Structure from Motion (SfM) method for which no sophisticated equipment is needed. The most important technical component of the system is basic digitalSLR camera.

## Working process

The Structure from Motion method is a designation used for the reconstruction of three-dimensional points from two-dimensional digital photographs i.e. calculated by comparison of different distances from a plurality of image points on at least two images, given relative location and orientation. If these common points are known, then a very fine three-dimensional point cloud can be calculated from the total image information. The first issue one has to deal with when it comes to the 3D capturing is a user preference of the final rendered output versus the software default treatment. While for the process of computing hard shadows represents a clear advantage, an archaeologist prefers neutral light which enables better scientific evaluation. Elimination of hard shadows may be achieved by a higher number of shots (which is especially important in the monochrome environment of Sudanese steppes and semi-deserts in which most of the ancient sites are set). Suitable moments for photographing present themselves only twice a day. Shortly before sunrise and shortly after sunset the light is diffuse enough not to create shadows, but at the same time strong enough to reveal all the details. As the favorable conditions do not last for long, the photographer has to adequately plan the site's documentation in advance with the technology of the software's reconstruction methods in mind.

The software searches for an identical pixel constellation on two different pictures, preferably with confirmation of coordinates by means of a third picture. The pictures should be taken from different locations so that the software is able to compute the mutual position of the locations from where the photographs were taken – e.g., taking panorama photographs from a single location would not generate a useful result (Fig. 4). The software needs a number of photographs taken from different positions but in the same bearing. One has to take a series of parallel image captures (ideally in the upright position towards the sampled object or structure; Fig. 5).

9 Cf. Vacek / Dašková / Onderka 2013.
10 Cf. Warren 1999, Bear / Livingston / Fitz 1998; the conservation of mud-brick structures also cf. publications of the Earthen Architecture Initiative and of the Getty Conservation Institute.
11 Kleinitz / Rüther / Näser 2010.

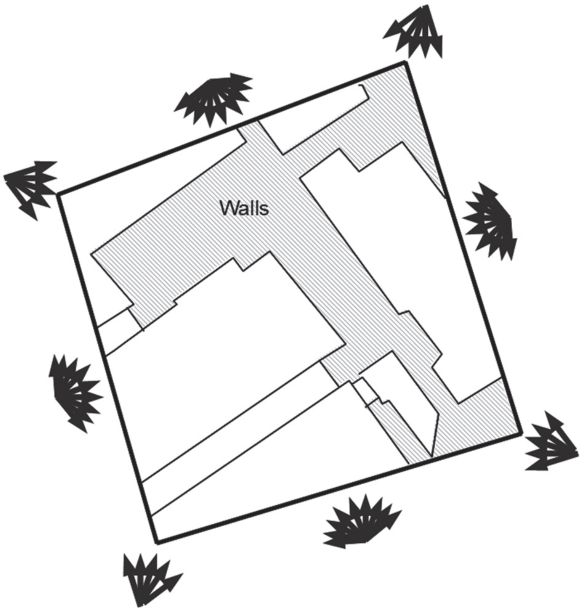



Fig. 4: Example of false photograph sampling of an excavation square (author).

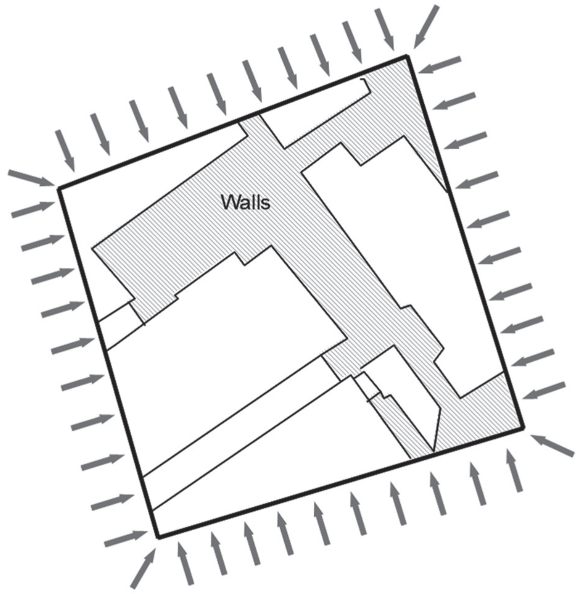



Fig. 5: Example of correct photograph sampling of an excavation square (author).

The parallel captures would be sufficient given that the object has hard contours. However, if the scanned object is monochrome, the software requires more sets of pictures from the same bearings. The software uses them to verify its computations of point clouds from different directions. An inclusion of visually diverse landscape features (e.g. bushes, trees, bigger stones, etc.) behind and around the documented structure is of important help in the alignment of point clouds.

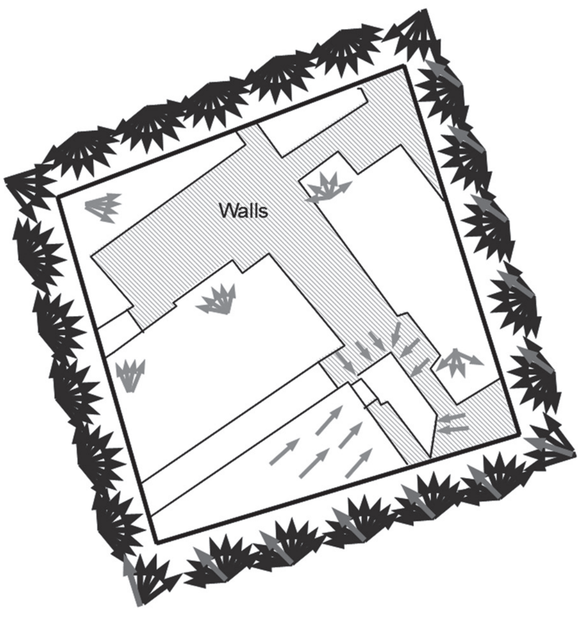



Fig. 6: Photograph sampling of complex structures within an excavation square (author).

In the case that complex structures with many edges or small curve details are included, one should take additional photographs of these details from within the space in question, but only after the general capturing has been completed. This is to avoid inclusion of traces of the photographer in the photographs. One has to pay attention to approach a section with details step by step so that the software is able to locate this section within the documented space (Fig. 6). Once the picture capturing is finished, the next step is to process the images with the software.

## Software

Various commercial and open-source software applications relevant for the method are currently available in the market. The advantages of the commercial ones rest in the fact that they are provided as a ready-made product. However, one downside is that these make the user dependent on the services of the provider, especially when it comes to updates and technical support. This dependency may be solved by use of an open-source software bundle. One can see two important advantages of this solution: firstly, there is large online technical support base within open-source community forums; secondly, this community shares their experiences which results in further improvement of the software.

The open-source programs are – in contrast to the commercial ones – usually good only for one or more individual steps in the whole process, but

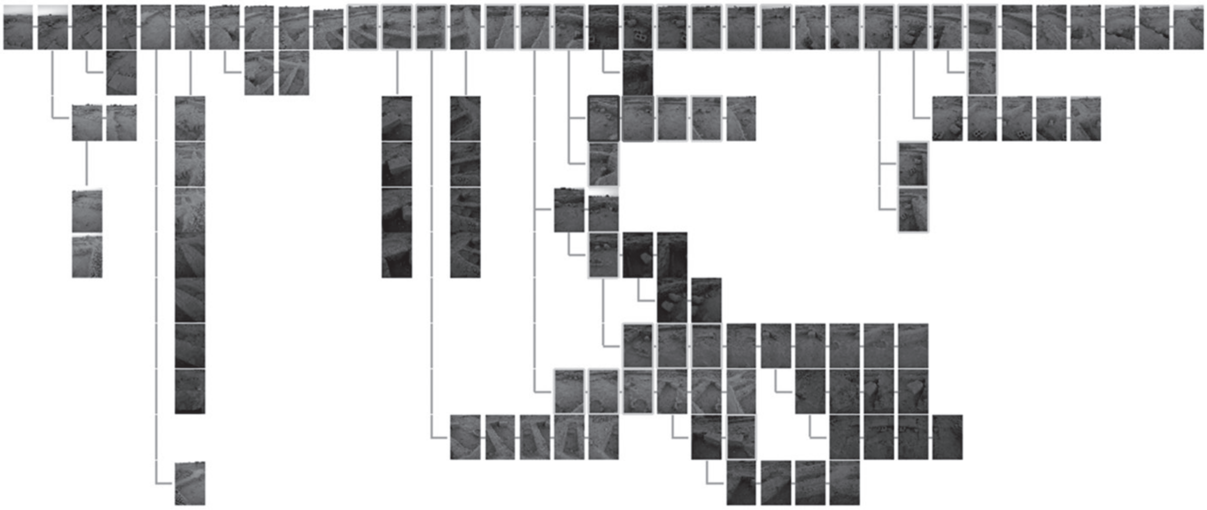


Fig. 7: Spanning tree network showing relations between individual digital photographs.

not for its entirety. In this particular case, the steps include [1] matching of pictures, [2] creation of a dense point cloud, [3] geo-referencing (optional), [4] surface reconstruction and [5] application of the surface texture on the model. Most of these steps require a computer with high capacities to handle large amounts of data.

An alternative for bypassing the above-described gradual process is offered by a number of open-source providers. Pictures are sent to the provider's internet server where an algorithm computes the model which is sent back to the customer. However, the automatic character of computing prevents the customer from controlling the whole process and the processed data output. The quality of the final outcome hence cannot be guaranteed and additionally, copyright issues concerning both original photographs and the model itself may arise. This alternative does not pose such heavy demands on computer equipment.

## Case study

For the processing of data gained within the framework of the Archaeological Expedition to Wad Ben Naga, VisualSfM software invented by Changchang Wu of the University of Washington was used.[12] Its functions cover steps [1] to [3]. The remaining two steps, [4] and [5], we processed with the Meshlab program which is widely used for 3D processing.[13] Comprehensive technical documentation and manuals exist for both programs.[14]

The pictures to be processed are first loaded into VisualSfM. All needed settings may be changed in an initialization file, including adjusting the software to the capacities of a particular computer e.g., resizing the downloaded images or reducing the number of pictures used for computing points from the standard of three to two (note this is not advisable because of possible deformation caused by the hot air and the dust particles it includes). For precise settings, one can consult detailed documentation. Once the images are loaded, the matching of points may proceed. During this step VisualSfM compares all pictures with each other and computes their positional relationship. The result is the so-called spanning forest (Fig. 7) with a basic point cloud that presents the first overview of how the computed points stick together (Fig. 8). In this moment the software sets mutual positions of all images. The next step follows the so-called dense reconstruction. In that phase, the software uses a special algorithm of a Patch-based Multi-view Stereo Software (PMSV). Based on the acquired information concerning the alignment of images, the software may proceed to the creation of a fine point cloud. Following its reconstruction, the cloud may be scaled. At this point, the digitized cloud may be correlated with georeference systems, including total-stationing, GPS, etc. (Fig. 10), which enables real distances within the model to be measured. At this point, it is also possible to merge indi-

12 Wu 2013.

13 Cignoni *et al.* 2008.

14 VisualSfM:http://homes.cs.washington.edu/~ccwu/vsfm/doc.html (last visited 31.08.2013); Meshlab: http://www.cyi.ac.cy/system/files/MeshLab%20Documentation1.pdf (last visited 31.08.2013).

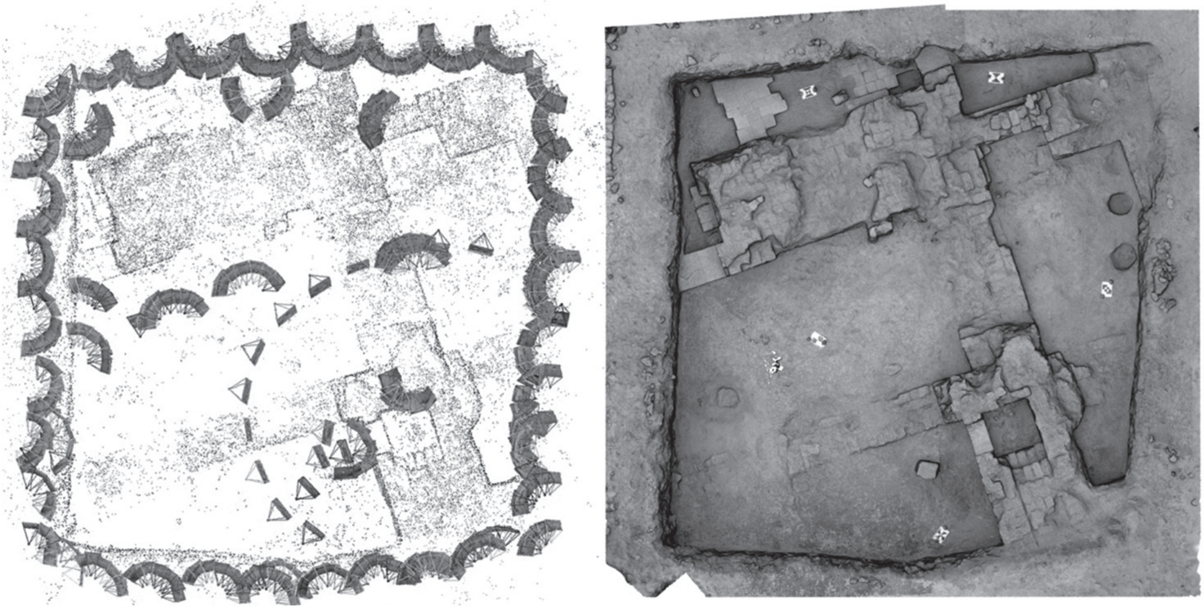


Fig. 8–9: Visual comparison of the point cloud of missing matches computing and the finished surface model.

vidual models created in the above-described way into a single one (e.g. individual squares). At the end of the transformation, VisualSfM will also give an error ratio that shows the accuracy of models and geo-reference.

The next step following the completion of the point cloud is the transformation into a surface model. The step may be still carried out in VisualSfM, but MeshLab and particularly its function "Poisson surface reconstruction" has proven to be a more efficient tool. In the fourth step, all points are meshed into a surface consisting of triangles. The outcome is a surface coexisting with the point cloud. The newly created surface is at that moment without a color parameter which is only gained subsequently through the "vertex attribute transfer" from the point cloud (Fig. 9). The final step usually consists of cropping the model's edges (as the model usually extends behind the limits of the intended documented area).

## Experience from Wad Ben Naga

As already stated above, the 3D capturing method was first employed at Wad Ben Naga during the Expedition's fifth season in winter 2012. The method was used during the exploration of the so-called Typhonium (WBN 200; Fig. 11), namely on three squares with a side of 10 m (T6, T8 and T10) that revealed remains of the proper temple, including parts of the main sanctuary (WBN 201), a portico (WBN 202) and an open courtyard (WBN 203) that immediately adjoins the temple's pylon. The walls of the temple consisted of a mud brick core and red-brick casing. Sandstone was used for the paving

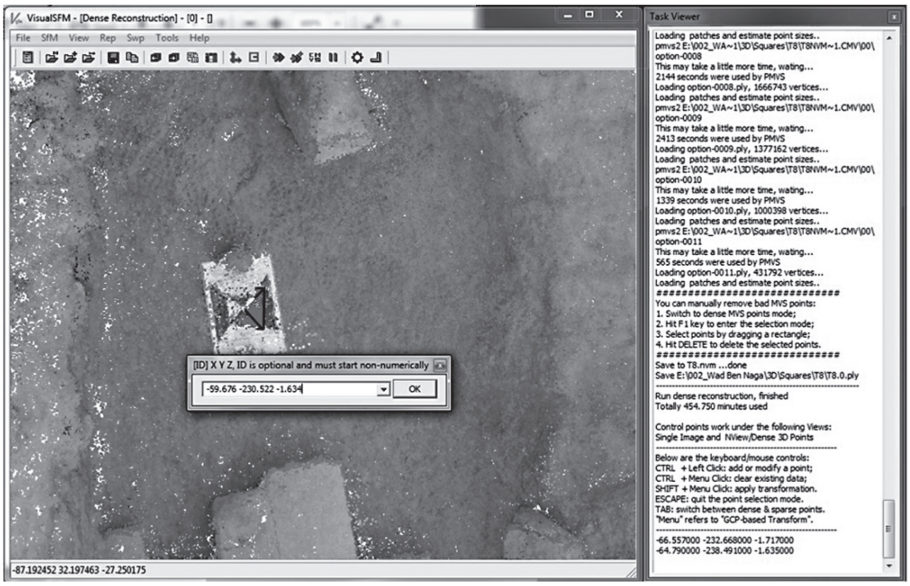
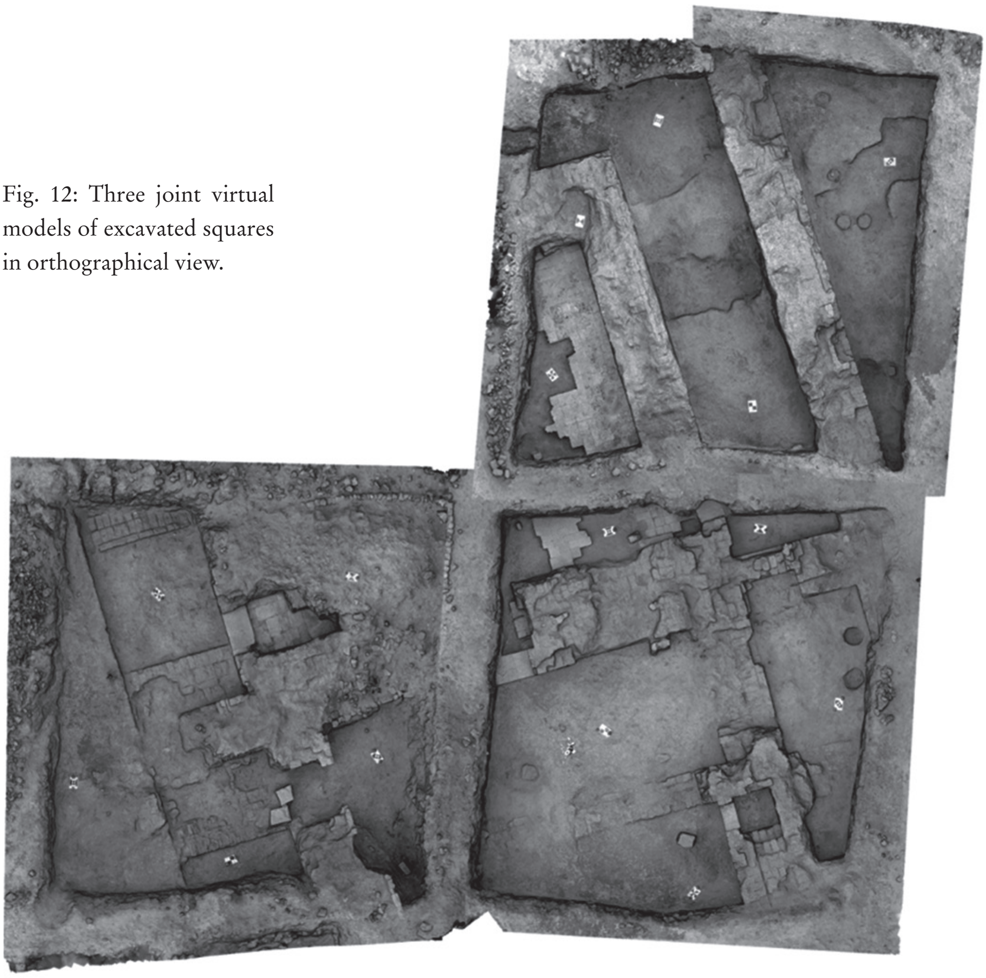



Fig. 10: Geo-referencing of the point cloud in VisualSFM

Fig. 11: Remains of the so-called Typhonium.

Fig. 12: Three joint virtual models of excavated squares in orthographical view.



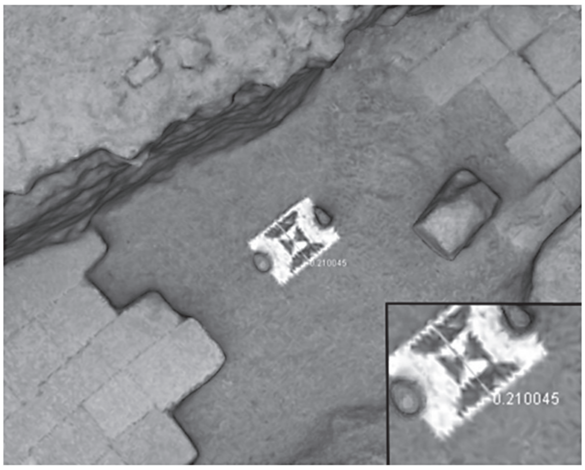



Fig. 13: Measuring of the accuracy of the three-dimension model according to a reference point (on A4 format plate).

of the main sanctuary's floor and thresholds, door jambs and architraves.

Each square was documented through 400 to 600 image captures. The creation of the model of individual squares took around 20 hours. During the documentation, reference points were fixed by the total station to the local leveling grid system. This georeference later enabled the individual models to be merged together automatically (Fig.12), and it also made it possible to establish the accuracy of measuring (Fig. 13).

In the following season (spring 2013), the 3D documentation of the squares at the Typhonium site continued as an integral part of the excavation process. At the same time, the Expedition decided to carry out limited excavations of the so-called Circular Building (WBN 50; Colour-Fig. 8). The structure had been discovered during the first excavation season of the Sudanese Antiquities Service Expedition in the winter of 1958/1959. Ever since, the structure has been exposed to weathering and it underwent several revising excavations and surveys. However, none of the excavators ever produced accurate documentation of the structure. The structure, which awaits conservation, was thus documented in the best possible manner available to us at the given time.

The structure has a circular groundplan with a diameter of 18 meters. A ramp adjoins the structure from the northwest. The produced model also included the immediate vicinity of the structure. For the digitization about 1400 digital photographs were taken and the processing in the computer took three long days. But the final virtual model provides additional possibilities, including the creation of cross-sections, an inner view etc. (Colour-Fig. 9-10; Fig. 14).

## Summary


The results of the Structure from Motion method's employment have proven to be highly satisfactory for the needs of our Expedition. The results have been cross-checked with other documentation methods used by our team, such as total-stationing, GIS and traditional manual documentation. As has been noted above, comparison of this method with other techniques of scanning at the site, such as laser scanning, was not pursued as the conditions prevailing in the Sudan are adversary to such techniques.[15] The use of the scanning method requires some basic training both in the field and in the software applications; however, this should not be seen in any case as an obstacle preventing an archaeological team from using the technique in routine archaeological exploration.

Besides providing invaluable data for the excavator, the method serves as a great tool for the work of site conservators, as well as for the documentation of a site's cultural heritage. With regard to the ongoing and upcoming conservation projects at the site connected with the future addition of the site of Wad Ben Naga to the serial cultural property of the Archaeological Sites of the Island of Meroe, listed on the UNESCO World Heritage List, the technique enables us to document the present state of the ancient monuments at the site and, based on comparison with later scans, determine the dangers the sites faces.

The Structure from Motion technique will definitely find its use in other spheres than those previously defined (i.e. structures, squares, etc.), as extensive cemeteries are located to the north and to the south of the ruins of the Meroitic royal city at Wad Ben Naga.

Due to the ongoing industrial progress of the Republic of the Sudan, the mission had to carry out some rescue surveys in the past (e.g. at the site of Idd el-Baggar16). This method would perfectly serve the purpose of those situations when generally not enough time for standard archaeological work is available.

The present writer strongly believes that the described method will be soon employed in routine archaeological field work in the Sudan on an everyday basis without requiring heavy financial demands on archaeological missions.


15 For the comparision of the laser scanning and Structure from Motion method cf. Studnicka et al. 2013, De Reu *et al.* 2013.

16 Onderka – Dufková 2011.

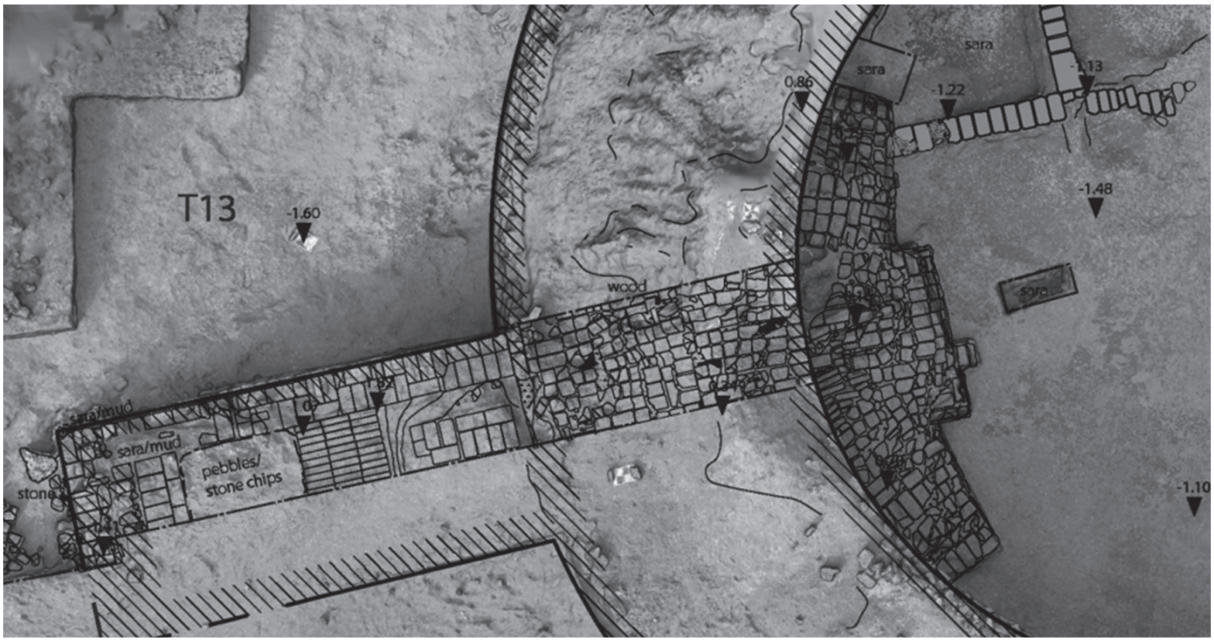



Fig. 14: A traditional drawn plan superimposed on the three-dimensional model of the Circular Building.

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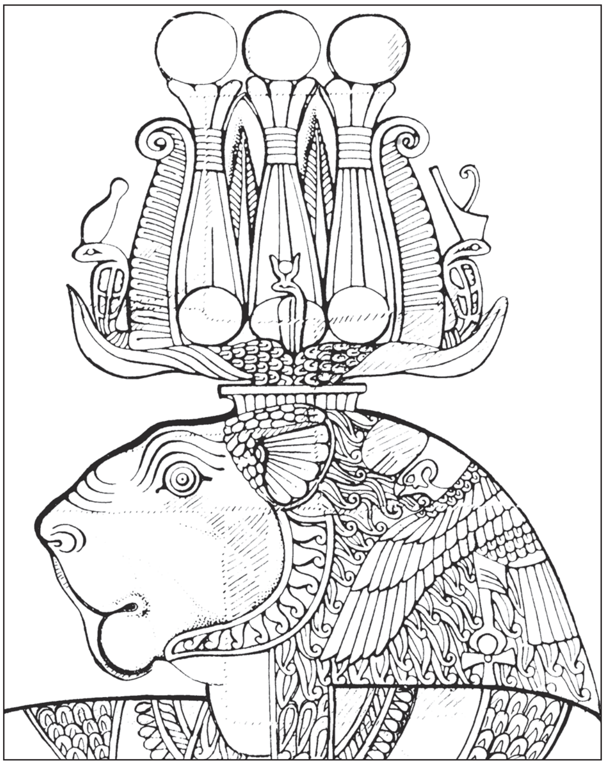
Zusammenfassung

Seit 2009 gräbt ein Archäologenteam des tschechischen Nationalmuseums im sudanesischem Wad Ben Naga. Da die antiken Gebäudestrukturen zumeist aus ungebrannten Lehmziegeln errichtet wurden, musste eine möglichst schonende und schnelle Dokumentationsweise aktueller Grabungsbefunde gefunden werden, ohne die Baustrukturen unnötig lange frei bewittert offenliegen zu lassen. Dieser Artikel beschäftigt sich daher mit der Low-Cost-Erstellung virtueller 3D-Modelle von architekturgebundenen Grabungsstrukturen im Rahmen der laufenden Grabungskampagnen in Wad Ben Naga. Ziel der Fallstudie ist eine kosteneffektive Einbringung der „Structure from Motion (SfM)“ - Methode in den archäologischen Grabungsalltag, jenseits von investitionsstarken Einzelprojekten. Dabei werden detailierte 3D-Modelle auf der Basis von digitalen Photographien erstellt. Besonderes Augenmerk wird vor allem auf die Anwendung von Programmen aus dem OpenSource-Bereich gelegt, welche für Forschungszwecke im Internet zur freien Verfügung stehen. Der offene Zugang zu den technischen Möglichkeiten, 3D-Modelle der aktuellen Grabungsergebnisse zu erstellen, bietet neben der großflächigen Visualisierung des gesamten Grabungsgeländes und anschließender Präsentation, vor allem in Kombination mit konventionellen Dokumentationsmethoden, wie Vermessung, Zeichnung und Photographie, eine breite Grundlage für Forschungen auch zwischen den Kampagnen. Weiterhin werden trotz geringem Kostenaufwand umfassende Informationen zur Bewahrung des antiken Kulturerbes erfasst und können anschließend einem breitem Publikum zugänglich gemacht werden. Im Artikel werden sowohl Erfahrungen berichtet, als auch der Arbeitsprozess mit Hinweisen erläutert und am Fallbeispiel Wad Ben Naga mit aktuellen Ergebnissen dargelegt.

# Mitteilungen der Sudanarchäologischen Gesellschaft zu Berlin e.V.



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SUDANARCHÄOLOGISCHE GESELLSCHAFT ZU BERLIN E.V.

Angesichts der Tatsache, daß die globalen wirtschaftlichen, ökonomischen und politischen Probleme auch zu einer Gefährdung der kulturellen Hinterlassenschaften in aller Welt führen, ist es dringend geboten, gemeinsame Anstrengungen zu unternehmen, das der gesamten Menschheit gehörende Kulturerbe für künftige Generationen zu bewahren. Eine wesentliche Rolle bei dieser Aufgabe kommt der Archäologie zu. Ihre vornehmste Verpflichtung muß sie in der heutigen Zeit darin sehen, bedrohte Kulturdenkmäler zu pflegen und für ihre Erhaltung zu wirken.
Die Sudanarchäologische Gesellschaft zu Berlin e.V. setzt sich besonders für den Erhalt des Ensembles von Sakralbauten aus meroitischer Zeit in Musawwarat es Sufra/Sudan ein, indem sie konservatorische Arbeiten unterstützt, archäologische Ausgrabungen fördert sowie Dokumentation und Publikation der Altertümer von Musawwarat ermöglicht. Wenn die Arbeit der Sudanarchäologischen Gesellschaft zu Berlin Ihr Interesse geweckt hat und Sie bei uns mitarbeiten möchten, werden Sie Mitglied! Wir sind aber auch für jede andere Unterstützung dankbar. Wir freuen uns über Ihr Interesse!
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