# Geodetic surveying as a tool for discovering the prehistoric settlement in Sudan (the 6$^{th}$ Nile cataract)

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## Abstract

*Surveying is an important part of any archaeological research. In this paper we focus on the archaeological research in north Sudan (6$^{th}$ Nile cataract) and the surveying methods applicable under the local conditions. Surveying in the Third World countries is affected by the political situation (limited import of surveying tools), local conditions (lack of fixed points, GNSS correction signal), inaccessible basemaps and fixed point network. This article describes the methods and results obtained during the three archaeological seasons (2011 – 2014). The classical surveying methods were combined with KAP (Kite Aerial Photography) to obtain the desired results in form of archaeological maps, detailed orthophoto images and other analyses results.*

**Keywords:** Sudan, 6th Nile cataract, surveying, KAP, methods

## 1. Introduction

The Czech Institute of Egyptology has conducted research on archaeological concessions in Sudan (6$^{th}$ Nile cataract) since 2009 (Lisá et al., 2011; Suková – Cílek, 2012; Suková – Varadzin, 2012). This archaeological concession is located approximately 80 km downstream of Khartoum. It covers nearly 40 km of the west bank of the Nile and includes the whole western part of the Sabaloka Mountains and the zone is *ca.* 10 km in breadth extending from the riverbank towards the west and north-west (see Fig. 1). The interdisciplinary exploration of this area is aimed at a better understanding of the occupation of the Sabaloka Mountains and its vicinity during the Mesolithic and Neolithic periods (8$^{th}$–4$^{th}$ millennia BC) and its interaction with the (changing) environment.

An integral part of the archaeological research is documentation by a variety of geodetic methods. The total station in combination with GPS measurements and Kite Aerial Photography was used for the surveying of the archaeological sites and features and topographic elements (such as terrain, settlements, paths). The results of the surveys are plans and archaeological maps, which supplement the satellite images of the research areas. Due to the absence of a fixed geodetic network and the GNSS correction signal, the survey was performed in a local coordinate system and even standard surveying procedures had to be adjusted from time to time to suit the local conditions. The objective of this article is to present the surveying methods applied in the extreme conditions of the Sudanese desert and the results achieved.

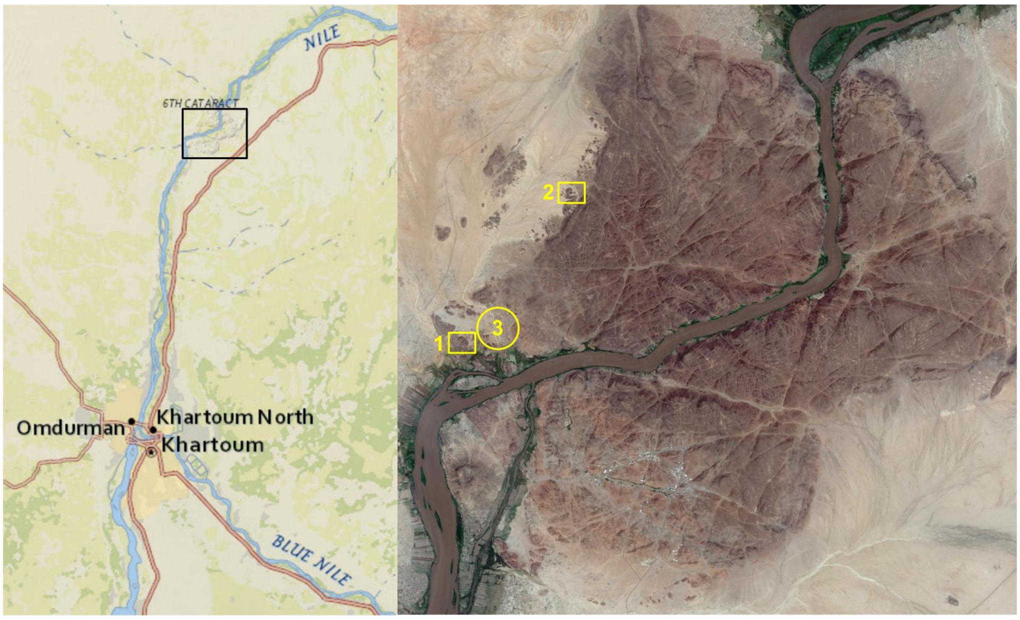


Figure 1: Area of interest overview (Sabaloka game reserve): 1 - the Fox Hill locality, 2 - the Sphinx Locality, 3 - prehistoric lake in the Lake Basin (basemaps: left – ESRI, right – Google).

## 2. Surveying conditions in Sudan

### 2.1. Importing surveying equipment

The Republic of South Sudan became independent in spring 2011. Since this period, the Republic of Sudan has applied very strict rules for the import of all surveying equipment (and many more things). All of the equipment (total station, GPS receivers, walkie-talkies) is subjected to special taxes. Permission issued by the Surveying Department in Khartoum allowing the usage of imported equipment may be required. The price of the permission depends on the type of imported equipment. Importing walkie-talkies (for long distance surveying) is not recommended as an additional permission from the Ministry of Communication is required.

### 2.2. Basemaps and satellite imagery

All of Sudan is, according to (Ali, 2009), covered by the Anglo-Egyptian Sudan Map Series, scale 1:250 000, created in the period of 1936-1951 by the United Kingdom Directorate of Overseas Survey. These maps are stored at the Survey department in Khartoum and they contain topographic layers together with approximate position of benchmarks and triangulation points. Other topographical maps available in our area of interest are maps 1:200 000, made by the Soviet Union in 1971. A more detailed map, is the one issued by the Sudan Survey Department in scale 1:100 000 – this map series was prepared in cooperation with the United Nations Development Program and it covers selected areas of the country (see Fig. 2).

There are no large scale maps available for the areas of interest, thus satellite imagery was used to identify terrain objects, possible settlement areas and for navigation purposes. The


Figure 2: Area of interest presented on a 1:100 000 map.

WorldView 2 panchromatic (spatial resolution in nadir 0.46 m) and multispectral (resolution 1.8 m) imagery were chosen as a suitable data sources for research purposes. The data obtained, were further processed using the *pansharpening* method. With respect to the price of the data, only the core areas were covered by the WorldView 2 imagery at the Sabaloka site.

The entire area of the research site at Sabaloka (covers nearly 40 km of the west bank of the Nile and includes the entire western part of the Sabaloka Mountains and the zone ca. 10 km in breadth extending from the riverbank towards the west and north-west) was covered by satellite imagery accessible by Google Earth, handpicked and saved directly from the application. All the images were stitched together using a panorama stitching software into a seamless image. The produced image is not registered to any coordinate system.

Navigation in an unknown terrain required an easy way how to transfer registered satellite imagery into a rugged Garmin GPS receiver. The new Garmin BirdsEye Satellite Imagery was used in this case, it offered the same quality as it is accessible in Google Earth for our areas of interest. This was very helpful while moving within the Sabaloka mountains.

### 2.3. Coordinate system and geodetic control network

In Sudan, one can encounter many different coordinate systems – Adindan, 1942 or WGS84. Adindan is a geodetic datum suitable for use in Eritrea, Ethiopia and Sudan. Adindan references the Clarke 1880 (RGS) ellipsoid and the Greenwich prime meridian (GeoRepository, 2015). The 1942 coordinate system is used in the Russian maps 1:200 000 and WGS84 is used worldwide for the GPS NAVSTAR.

The coordinates of the archaeological sites were obtained from NCAM (Sudan National Corporation for Antiquities and Museums) in the Adindan coordinate system without any metadata. This coordinate system was identified in ArcGIS (ESRI corp.) as Adindan_UTM_Zone_36N and the data could be properly transformed into WGS 84 and used for navigation using a common Garmin GPS.

The geodetic control network at the Sabaloka locality was explored in the Survey department in Khartoum, but the closest benchmark and triangulation point on the west bank of the Nile is located in Obdurman (ca. 70 km upstream). Fixed points on the east of the Nile were closer, but located in a highly secured military area. Based on these facts, local coordinate systems were established.

## 2.4. The local geodetic control network

The absence of a geodetic control network at Sabaloka resulted in the creation of a local geodetic network covering all areas of interest – the total area where the surveying tasks were performed is larger than 400 ha. The terrain at Sabaloka is very complex, with hills, large rocky structures and flat desert planes making the surveying difficult.

Figure 3: Points used as ground control points in the KAP survey (left), discrete fixed points (right).

The archaeological research begun in autumn 2011 at the Fox Hill locality (SBK.W-20/B) (Suková – Cílek, 2012; Suková – Varadzin, 2012) and here the beginning of the local coordinate system was situated. The coordinate system was initially meant to be used only for Fox Hill and the close neighborhood. The imprecise GPS measurements made it impossible to compare the elevation characteristics of the other archaeological sites within the Czech concession – thus the same coordinate system was “transferred” into all areas of interest.

Altogether 21 fixed points were established within the Fox Hill and the Sphinx (SBK.W-60) localities. All measurements performed in this area were based on these fixed points. The fixed point establishment was performed in 2012 by colour painting on selected rocks as the hills in the surroundings are made of friable granite. In the beginning of 2014, almost no fixed

Figure 4: Fox Hill locality and the surroundings.

points were identified as the extreme weather conditions destroyed the paint. The renewal of the local geodetic network was a crucial part of the 2014 expedition as incorporating the measurements from the past seasons with the current results was highly desirable.

## 3. Surveying instruments and tools

The most important imported surveying tool was the total station Leica TCR 303 (see Fig. 5). Two types of GPS receivers were used during the archaeological research – GPS Trimble Juno ST and Garmin GPSMap 62s. Despite of the lack of the GNSS correction signal, GPS usage was limited. GPS is mainly used for marking points of interest (settlement marks, important objects, terrain formations) discovered during the archaeological research in the wide area of the Sabaloka Mountains, marking the geodetic control network points as it is not easy to identify them in the rocky area, navigation to archaeological sites defined by NCAM and for navigation in the unknown terrain.

Figure 5: Surveying at the Sphinx locality (photo: L. Varadzin).

Figure 6: The Picavet suspension used on the Rhombus kite.

Kite Aerial Photography (KAP) was applied during the last archaeological season (autumn 2014). Small Format Aerial Photography is produced by KAP (Aber et al, 2010) which is usable for 3D models and orthophoto creation. KAP may be used as a supplement for UAVs (drones) in regions where their usage is forbidden. KAP has been successfully used in archaeological research in Africa many times (Bitteli, 2001; Brůna, 2013; Chagny – Hesse, 2007; Żurawski, 1993, 2005)

The one-string kite Elliot Rhombus Mega Power Sled, 300 × 170 cm, string length ca 200m, wind range 2 – 5 Bft and reinforcements GFK 2mm was used for the KAP survey. The same kite system was used with great success at archaeological sites at Abusir, Egypt (Brůna, 2013). The Picavet suspension (Verhoeven et al., 2009) is used to carry the camera used for SFAP (see Fig. 6). The camera holder was originally designed for a Canon Power Shot D10 camera with a mechanical trigger shooting images every 10 seconds. The 10 second shooting interval made this camera inappropriate for surveying large areas. A GoPro Hero 3+ camera was used instead. GoPro is a wide-angle, watertight camera with a 12MPix sensor and electronic shutter allowing time lapse images at a defined interval (2 second interval was used in this case). This camera is not primarily designed for SFAP (as it is equipped with a rolling shutter), but concerning its weight/pixel count/durability and based on our previous tests, this camera best served our needs in the KAP survey.

Other integral parts of the archaeological documentation are the simple measuring equipment which effectively support the surveying instruments. These are measuring tapes on a wheel of length 20 m and 50 m, tape rules (2 m or 5 m), folding rules (2 m), plummets, surveying stakes, strings for the delimitation of an archaeological squares, etc.

### 3.1. Surveying methods and precision

The total station Leica TCR 303 in combination with a surveying prism on a telescopic pole was used for the most of the mapping tasks. The range of the TCR 303 is maximally 2500 m and the longest sight lines within the archaeological mapping did not reach 1500 m. The total station is equipped with a program for computation of the free station method, measurements of minor geodetic points and indirect distance measurements. The methodology of “surveying

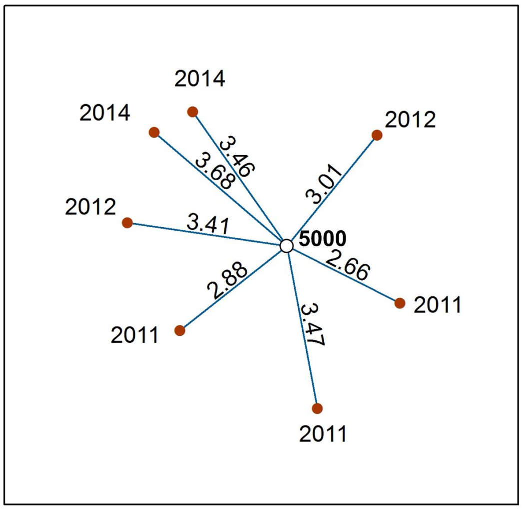


Figure 7: The initial point 5000 of the local coordinate control network (left). The control measurements on point 5000 during the archaeological seasons 2011, 2012 and 2014. The calculated distances are in cm (right).

in the desert" was many times proven during other archaeological expeditions in Egypt. See Brůna (2013) for more details.

The surveying conditions are much different from well-known European standards. The lack of a geodetic control network makes the surveying even more complicated and standard surveying workflows can't always be followed. Another factor is time stress – despite the expedition's time schedule and the surveying tasks time demandingness, all of the tasks had to be performed on the first attempt. This was a problem when making long-distance measurements. Long distance measurements are used while transferring the local coordinate control network to other archaeological sites in the area of interest. The measured distances were ca. 1000 m long and communication between the surveyor and the telescopic pole operator is problematic. Walkie-talkies normally used in Western countries, but are forbidden in Sudan – thus special flag signals (in combination with binoculars) are used to check whether the surveyor or the pole operator is ready to perform the measurement.

There are also several facts as well that may influence surveying precision. The imported total station may be stored in a custom warehouse for several days. Based on our experience, the goods stored in the custom warehouse were not always gently handled. The total station had to be checked and some basic calibration performed prior to surveying in the field.

Other facts influencing precision are the total station and the telescopic pole centering uncertainties - the fixed points are (with respect to the granite stones and rocks) marked by ca. 4 cm thick lines (see Fig. 7). Points established by the iron pipes (see Fig. 3, left) were built at the end of the 2014 season to preserve the points for further use. The vertical position of the telescopic pole is another crucial factor of the measurement but the set for the three-tripod system, suitable for long-distance measurements and fixed point establishment, is impossible to import into Sudan.

While transferring the coordinate system into other localities an oriented traverse is used.

Under standard conditions, such a long traverse should be oriented and connected on both ends to preserve the measurement precision. In the desert, we were forced to make the traverse only one side oriented and connected. Using this method will secure a sub-decimeter precision in the Z coordinate in-between the archaeological sites required for the Nile flood modelling. Transferring the coordinate system from Fox Hill to the Sphinx locality was the biggest surveying task. The traverse was almost 5 km long and 7 change points were used. This measurement lasted two days due to the rough terrain in which all the equipment couldn't be transported by a car.

The precision of the surveyed points was regularly checked by the control measurements on the established fixed points[1]. During every archaeological season, these measurements are performed to check the accuracy of the reconstructed fixed point network. An example is presented in Fig. 7, where the control measurements were performed on the initial point of the local geodetic control 5000 [1000, 1000, 377.87]. The measured coordinates are presented in Tab. 1. The RMS errors calculated based on these measurements are the following:

$$m_x = 0.020; \quad m_y = 0.021; \quad m_{xy} = 0.030.$$

Archaeologists required surveying precision (under these conditions) up to 5 cm, which was fully achieved.

Table 1: Point 5000 coordinates as measured during archaeological seasons 2011, 2012 and 2014.

| Year | X<br>1000.000 | Y<br>1000.000 | Z<br>377.870 |
|---|---|---|---|
| 2011 | 999.977 | 999.982 | 377.876 |
| 2011 | 1000.023 | 999.988 | 377.863 |
| 2011 | 1000.006 | 999.965 | 377.876 |
| 2012 | 1000.019 | 1000.023 | 377.880 |
| 2012 | 999.966 | 1000.004 | 377.874 |
| 2014 | 999.980 | 1000.028 | 377.873 |
| 2014 | 999.972 | 1000.024 | 377.877 |

Another task was to compute the KAP derived models accuracy. The results derived from the KAP survey are Digital Surface Models (DSM) and orthophotos. Here we may want to know the accuracy of the resulting 3D model. The derived raster DSM is compared with the points surveyed during the 2011 and 2012 season (see the Fox Hill case study chapter). The resulting differences should evaluate the quality of the data. All of the tested DSMs have differences of no larger than +/- 5 cm from the reference data. The larger differences are caused by the sparse surveyed points which do not describe all of the rocks and stone formations in detail.

## 4. General conditions

The general conditions are much different from Western World standards. The whole archaeological expedition is living in the same conditions as the locals, accommodated in a rented

[1] While measuring archaeological data, the points of the (local) fixed geodetic network in the surroundings are measured as unknown points to evaluate the measurement accuracy.

house near the archaeological site. The house is built of bricks dried in the sun and usually contains of two large rooms, a hall and a large back-yard (used as an open-space bedroom). Food is obtained from local sources and prepared by a hired Sudanese cook. Nile water is used for washing and cooking and bottled water for drinking. Electricity has been available since 2013, so the diesel generator used for charging all the equipment is no longer used.

Sunrise is about 6am and sunset about 6pm. Work starts usually at 7am and there is a lunch break from 12.30 pm to 3pm, as the weather is very hot during midday. High temperatures (over 50°C) are not suitable for the surveying equipment. Stronger winds sometimes bring dust and sand in the air and these conditions are not suitable for long distance measurements.

The local people are mostly friendly and hospitable, but the fixed points have to be marked in a very discrete way as a cross made on the stones by the *foreigner* means that there is gold hidden underneath. This has led to the destruction of fixed points on several occasions.

## 5. The Fox Hill locality (SBK.W-20/B)

The Fox Hill locality is the most important prehistoric site located within the Czech archaeological concession in the Sabaloka region. The site is structured on 16 terraces and platforms, the total surface area of which is 11,650 m$^2$ (Fig. 8). The terraces and platforms are well delimited by the exposed bedrock and boulders and vary in size, elevation and ease of access. The settlement is dated back to the Mesolithic (ca 9000 – 5000 BC) and Neolithic (5000 – 3000 BC) periods (Suková – Varadzin, 2012).

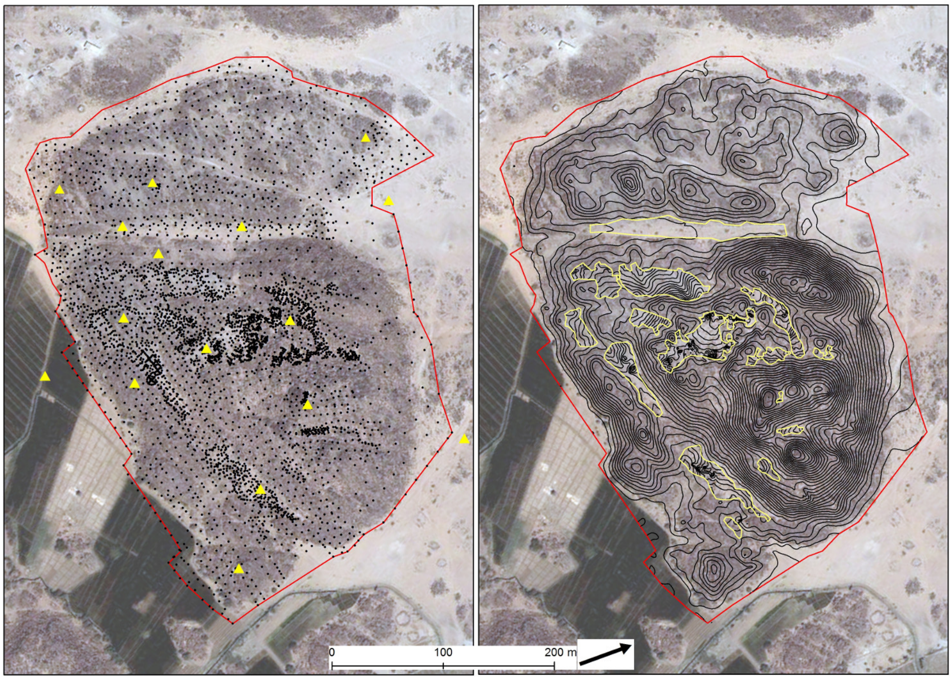


Figure 8: Surveyed points at the Fox Hill locality with marked fixed points (left). Contour lines generated from the DEM generated based on the surveyed points and the delineated occupation terraces (right). (Basemap: Google)

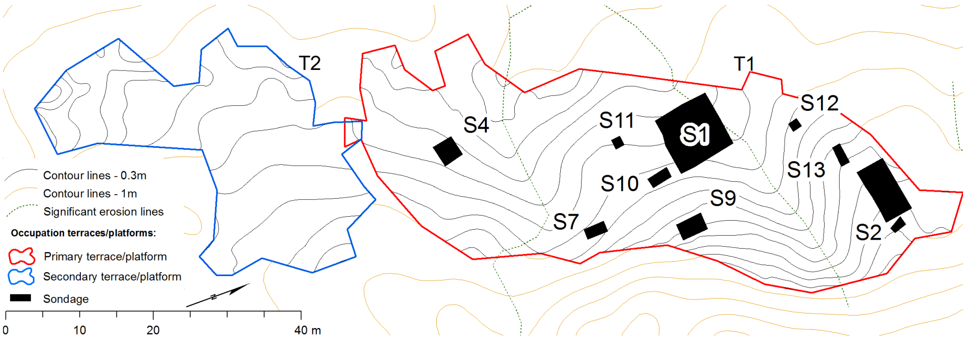


Figure 9: Detail of Terrace 1 and Terrace 2 at the Fox Hill locality.

At Fox Hill, 17 geodetic control points were established and more than 4500 points were measured. The occupation terraces are covered by a 1x1m point network and the rest of the area by a 5x5 m network, supplemented by points of erosion lines, ridges and significant stone structures.

Every site has its own specific environment, thus the choice of a proper interpolation method is required (Karel, 2006; Pacina, 2013). Based on previous results and tests, interpolation methods implemented in the ArcGIS (Topo to Raster) were used for producing a DTM of the localities.

Contour lines of a 0.3m interval for the occupation terraces and a 1m interval for other areas were derived from the interpolated DTM. See Fig. 8. The contour map may describe the spatial relationships between adjacent areas in the locality, material transportation caused by erosion (the archaeological soundings started in the areas that are not affected by erosion), and possible connections between the settlement areas and their elevation.

Delimitation of the occupation terraces at Fox Hill must be done by an archaeologist, as they recognize the boundaries of the terrace. An example of the delineated terrace, together with archaeological soundings is shown in Fig. 9. Fig. 11 shows objects excavated at Terrace 1 (T1), Sounding 2 (S2) in detail.

## 6. The Sphinx locality (SBK.W-60)

The Sphinx locality, positioned on a granite outcrop in the Rocky Cities area is the second most important site in the Czech concession. The outcrop features only one platform of 940 m$^2$ situated ca 15 m above the surrounding terrain. The surface finds at Sphinx attest to the occupation of this site only during the Mesolithic period (Suková – Varadzin, 2012).

Despite of the distance between the two localities it was decided to make a local coordinate system at Sphinx as well. The archaeologist requested a sub-meter precise comparison of the altitudes of these two localities in connection with the possible local flooding by Nile. A test using the Garmin GPS receiver was performed to define the altitude of the two known points previously measured with the total station. Altitude calibration was performed on one of the points and the other point several hundred meters away was then measured. The result was unsatisfactory – the difference in the altitude was almost 10 m. It was decided to put the Sphinx locality in the same local coordinate system as Fox Hill. This was performed by a *one*

Figure 10: Fox Hill - Terrace 1, Sounding 2 - excavated circular objects.

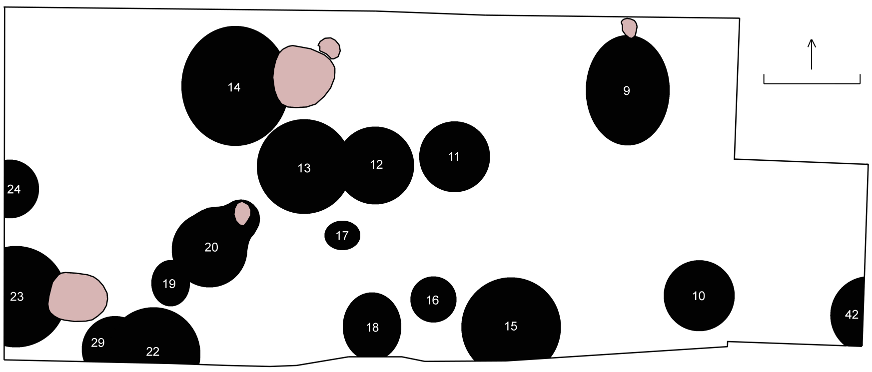


Figure 11: Objects excavated at Terrace 1, Sounding 2 – compare with Fig. 10.

*point oriented traverse* (7 points, 4.7 km length). Based on previous precision tests performed in this area; we may consider the precision of the applied method satisfactory.

Within the Sphinx locality, about 400 points on settlement terrace of ca. 900 m$^2$ (see Fig. 12) were surveyed. The resulting archaeological map is presented in Fig. 14 and the sounding excavated in season 2012, in Fig. 13. The archaeological map has a detailed orthophoto used as the basemap. This orthophoto was created using KAP and the Small Format Aerial Photography. Altogether more than 1300 images were taken during the KAP survey. The camera on the kite swung and thus only a small amount of the imagery could be considered horizontal and used for further processing. Only 60 images were used for creating the 3D model of the Sphinx locality and the derived orthophoto (presented in Fig. 14). Image processing was per-

Figure 12: The Sphinx locality with marked occupation terrace.

Figure 13: The Sphinx locality - research at Sounding 2 (2012).

formed using PhotoScan (Agisoft LLC) software. Detailed processing workflow is described i.e. in (Verhoeven et al., 2012).

## 7. Discovering a prehistoric lake – the Lake Basin locality

The Lake Basin area adjoins the massif of Jebel Sabaloka from the south west and extends over ca. 2.2 km x 1.5 km. This microenvironment is closely connected to the Nile, the waters of which used to submerge the lower reaches of this area during the annual floods in prehistoric times. This landscape type is formed of more than 20 mostly granite rock outcrops which vary in their size and in the number of natural terraces and platforms suitable for occupation (see Fig. 15). The former occupation sites are arranged around a depression where the remains

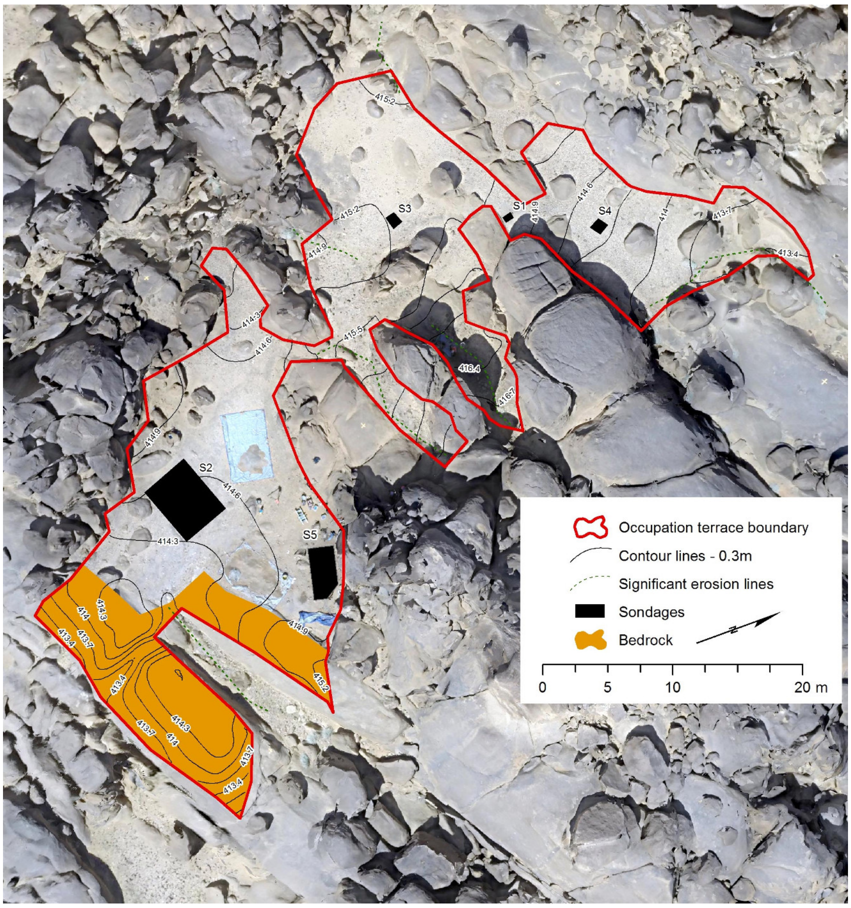


Figure 14: Archaeological map of the Sphinx locality.

Figure 15: Lake Basin with granite rock outcrops.

Figure 16: KAP in the Lake basin (Photo: J. Novak).

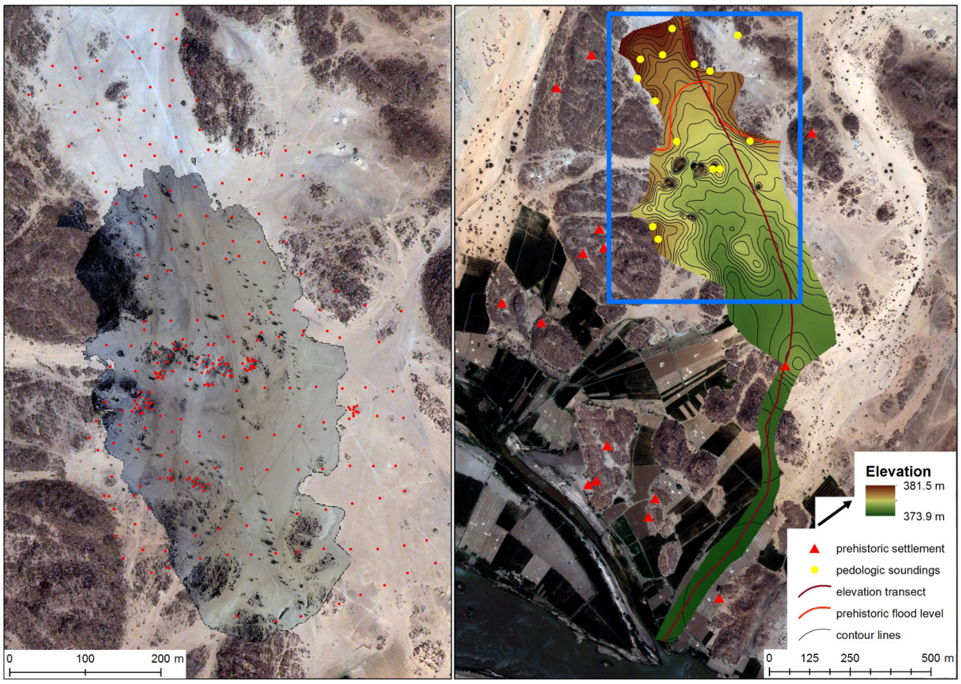


Figure 17: Point surveyed within the Lake Basin area and orthophoto derived from the KAP survey (left). The created DTM of the prehistoric lake bottom with locations of identified archaeological sites and sediment soundings. (Basemap: Google)


Figure 18: Orthophoto image created based on the KAP survey – marked sounding at the tumulus foot.

of a prehistoric lake were identified (Suková – Varadzin, 2012).

Since the 2012 season, it was desired to create a 3D model of the prehistoric lake bottom and prove the relationship with the Nile water level and potential prehistoric flooding. With respect to the natural conditions in the Sabaloka region, it is not easy to visually estimate elevations and distances. The lake bottom reconstruction has been done using several methods. In 2012, two transects were surveyed proving that this area could be flooded by the Nile. More effort was used to work on this topic in the 2014 season. The whole bottom of the potential lake (ca. 25 ha) was covered with a regular 25 x 25 m point grid and surveyed with the total station densified in the areas with a more complex terrain.

The KAP survey was used in the areas where the sediment samples were taken. The area of interest was surveyed twice as during the first attempt a very strong wind caused an uncontrollable kite fall resulting in camera damage. The second attempt went well, but it was proven that the KAP method is not suitable for covering such large areas, using the equipment used so far. The camera swings on the kite and a longer observation at one point is required to obtain horizontal images – this can be achieved in smaller localities but impossible at a 25 ha area. The oblique images in different directions "break" the point cloud computed by the Structure from Motion algorithms. More than 1600 images were taken during this survey and only 200 were finally used for the 3D model and orthophoto creation.

The area surveyed by the KAP method and covered with surveyed points is presented in Fig. 17. Based on all the obtained data, the DTM representing the former lake bottom was created. In Fig. 17 (right) the prehistoric settlement sites (occupation terraces) in the Lake Basin surroundings are identified. The altitude of these sites varies from 378 to 380 m.

Based on field research, it was determined that these settlement sites were (probably) not flooded during the seasonal Nile floods and thus this elevation value was used for modelling the level of prehistoric floods. Details of the resulting orthophoto image of the Lake Basin (with 3 cm/pixel resolution) are presented in Fig. 18. In the figure, the soil profile containing the original prehistoric lake sediments, protected from erosion by the tumulus is marked.

## 8. Conclusions

The modern methods of spatial data collection offer fast and quality data. Surveying in developing countries is a little different as new methods can't be imported (UAV) or properly used (GNSS correction signal). The surveying methods applied in the Sudanese desert are not absolutely fitting into Western standards but still offer the best possible results under these extreme conditions. In this paper, spatial data collection methods are presented used within the archaeological research that offer a new point of view on archaeological sites and findings. One interesting data collection method is Kite Aerial Photography that is used as an UAV supplement. We were capable of creating orthophoto and 3D models of the sites. 3D models created during the 2014 season are presented at https://sketchfab.com/jan.pacina/folders.

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