3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM

3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME

Richard Walters, Nadja Zupan Hajna

IZVLEČEK

V članku predstavljamo problematiko terestričnega laserskega skeniranja velikih naravnih jam na primeru Škocjanskih jam, ki so del Unescove svetovne dediščine. Glede na obstoječe podatke tahimetrične izmere jamskih rovov in iz njih izračunanih prostornin je bilo skeniranje tako velike jame velik izziv za ekipo. Jama s skoraj 6 kilometrov dolgimi rovi z dimenzijami približno 30 x 40 metrov in maksimalno višino do 145 metrov je bila skenirana s 370 stojišč. Postopek vključuje postavitev stojišč, prekrivanje skeniranja po progresivni poti in, ko so posnetki na površju, njihovo zbiranje, čiščenje in združevanje v 3D-model. Pridobljenih je bilo 8,3 milijarde točk in 2600 fotografij z visoko ločljivostjo. Za registracijo oblaka točk je bil uporabljen Reiglov program RiSCAN Pro, nato je bil oblak točk izvožen v 3D Hexagon Reshaper in izdelan je bil ploskovni 3D-model, iz katerega je bilo mogoče opraviti vse meritve in izračune. Za dodaten vir podatkov smo uporabili zajem podatkov s kamero brezpilotnega letalnika. S fotogrametrijo smo naredili digitalni model površja ter ga nato v 3D Reshaperju povezali z modelom jame. Podatki visoke ločljivosti modela točkovnega oblaka se lahko uporabljajo v različne namene, kot so izračun prostornine, odkrivanje geoloških in speleogenetskih oblik itd. Trenutno je Martelova dvorana s prostornino 2,55 milijona kubičnih metrov potrjena kot 11. največja jamska dvorana na svetu.

ABSTRACT

In this article, we present issues arising from Terrestrial Laser Scanning of large natural caves using the example of Škocjan Caves, a UNESCO World Heritage Site. Regarding pre-existing tachymetric survey of the passages and volumes calculated from them, the scanning of such a large cave was an even bigger challenge for the team. The cave of almost 6 km long passages with dimensions approx. 30 m x 40 m and max. heights up to 145 m, was scanned from 370 stations. Process of surveying the cave, involves establishing scanner positions through the cave, where scans will overlap, in a progressive route and once back on the surface, collecting, cleaning and stitching the scans into a point cloud 3d Model.3D model. A total of 8.3 billion points were captured and 2,600 high-resolution photos taken. With Reigl's RiSCAN Pro software, a point cloud model was registered and then exported to Hexagon's 3D Reshaper to create a full surface model from which all measurements and calculations were made. Additionally, data acquisition using a camera on an unmanned airborne vehicle was used. By photogrammetric approach, digital terrain model of a surface was built and then tied to the cave model within 3D Reshaper. The resulting high resolution - point cloud model may be used for various purposes such as: volume calculations, detection of geological and speleogenetical features, etc. With a volume of 2.55 million cubic metres, Martel's Chamber is confirmed to be the 11th largest cave chamber in the world at the moment.

KLJUČNE BESEDE

terestrično lasersko skeniranje, oblak točk, velike jame, prostornina, Slovenija

KEY WORDS

Terrestrial Laser Scanning, point cloud, large caves, volume, Slovenia

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 89 |

SI | EN

1 INTRODUCTION

A project of 3D laser scanning of the cave was carried out by the Karst Research Institute of the ZRC SAZU and the Škocjan Caves Park together with the members of the British Cave Association (BCA) in 2018 and 2019. Cave Škocjanske jame (Škocjan Caves, UNESCO World Heritage and RAMSAR) is 5.8 km long cave near Divača village (Classical Karst, SW Slovenia; Fig. 1). The river Reka sinks into Škocjanske jame at an altitude of 314 m a.s.l. The underground channel is after a few hundred metres interrupted by two large collapse dolines Velika and Mala dolina. Cave then continues with 2.6 km long channel to the Martelova dvorana (Martel's Chamber) at 214 m a.s.l. with an anticipated volume of 2.2 x 10^6 m³ (Drole, 1997). To obtain the volume of that chamber was a major objective and challenge for our team.

Over the last years, a few BCA members were aiming to scan the world's largest cave chambers in 3D using modern LiDAR scanning technology. A project to measure the 10 largest cave chambers of the world started in 2013 (Walters, 2016). They measured the biggest chambers of the caves in China (Miao Room, Cloud Ladder Hall, Hong Meigui, Funnel of Light), Malaysia (Sarawak Chamber, Api Chamber), Mexico (La Muneca Fea), Iran (Ghar-e-Dosar), Oman (Majlis al Jinn), France (Salle de La Verna), Spain (GEV Chamber), USA (The Big Room), Belize (Belize Chamber) and others. They presented their measurements at several conferences and 3D movie about Miao Room on the National Geographic channel (https://www.nationalgeographic.com/china-caves/supercaves/). The largest chamber volume of the world proved to be Miao Room, and it is 10.59 million m³, the second is Sarawak Chamber with 9.81 million m³, the largest in Europe is Salle de La Verna with 3.65 million m³ and stands as 9th of the world (Walters, 2017). While the volumetric data that could be obtained from LiDAR surveys is incredibly accurate, it was felt that quoting volumetric metrics to 2 decimals (*i.e.* 0.01 x 10^6 m³) reflected the issue that chamber boundaries are difficult to define consistently, there are issues in defining the exact boundaries of the cave chambers; therefore we have restricted quoting volume metrics to 2 decimal places (ie. 0.01 x 10^6m³).

The volume of Martelova dvorana was not team's only goal; we also wanted to get the 3D model of the whole cave to compare with the Institute's tachymetric survey in 1991-2002 and compare the new results with Institute cave map from 2015 (Drole, 2015). 3D point cloud would also be useful to detect geological structures, speleogenetic features and for its use to interpret speleogenesis of the cave. Additionally, a 3D model would be useful in the monitoring of all changes in the cave and also for tourist interpretations.

2 CAVE MAPS OF ŠKOCJANSKE JAME

The first map of the caves was drawn by Anton Hanke during the measurements in 1885. In 1913 Anton Meeraus published a map with all the previous measurements which was used until the tachymetric survey of the Karst Research Institute ZRC SAZU. The survey was carried out from the beginning of the 1990s to the year 2002 (Mihevc, 1994, 1995, 1998; Drole, 1997). Subsequently, various individual measurements of smaller passages were added by several caving teams. Notwithstanding the quality of Hanke's original survey conducted with the technology of the time, some errors in Hanke's measurements were discovered. After Hanke's measurements, the altitude of Martelovo jezero (Martel's Lake) was 175 m (Boegan, 1938), while the new measured value was 214 m. The second, even more important error,

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 90 |

was shown at the layout of the cave: the end of the cave (Martelovo jezero) actually lies 350 m northeast of the Hanke's ground plan (Mihevc, 1998). These errors in Hanke's map and later copied maps are important because all previous interpretations of speleogenesis and of the flow of underground river were based on them. The newest map was done for the purpose of monitoring the caves in 2015 (Fig. 1); additionally, the Škocjan Caves Park with the Institute completed and digitized map's different layers.
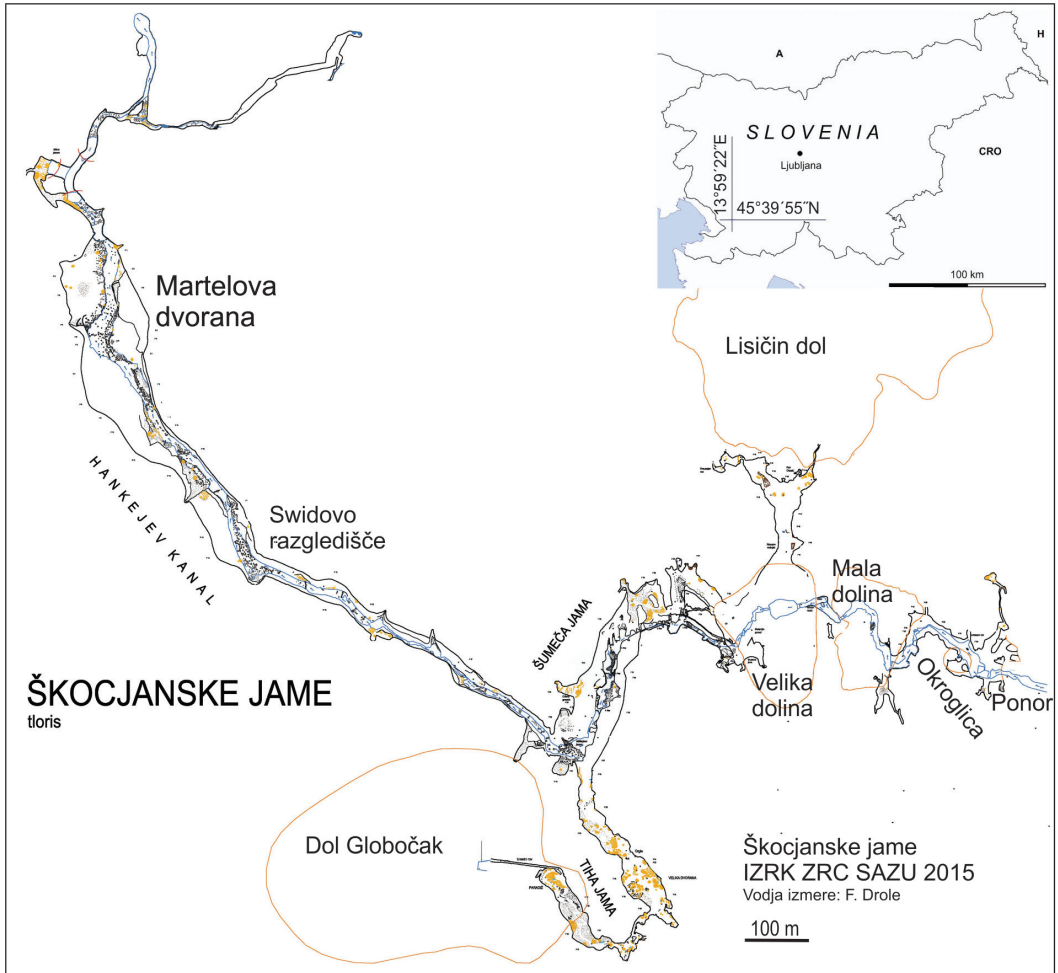

Figure 1: Cave map of Škocjanske jame (Drole, 2015; Karst Research Institute ZRC SAZU archive) with its location in Slovenia and position of Martelova dvorana.

The Institute also conducted several cross-sections of the cave passages using laser range finders, and the volume of the cave and its individual parts was estimated (Drole, 1997). After the measurements and calculations, the volume of the Martelova dvorana was about 2 million m³, with length 308 m (Mihevc, 1994; Drole, 1997), width 123 m and maximum height 146 m (average 106 m). In the main caves, Novaković et al. (2014) scanned Velika dvorana (Great Hall, Part of Tiha jama); they measured its highest point (30.82 m) and determined its average height (16.26 m).

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 91 |

3 METHODS

3.1 Terrestrial Laser Scanning (TLS)

Terrestrial Laser Scanning (TLS) was performed in a cave with a length of 5.8 km and passages' dimensions approx. 30 m x 40 m, and up to 80 m or even to 145 m high underground canyon with a flowing river in its bottom.

The Riegl VZ-400 laser scanner (Fig. 2) uses a near-infrared frequency of 1550 nm. It was chosen because it is a very robust 3D terrestrial laser scanner, which can reach 400 m and the can make measurements to within 5 mm at 100 m. It takes up to 300,000 measurements/sec with a recording width a vertical scan range of 100° and a horizontal scan range of 360°.

Figure 2: Cave was scanned by terrestrial laser scanner a.) Riegl VZ-400 during scanning (Photo F. Drole); b.) setup of the scanner at the station in the cave.

A sturdy 'survey-grade tripod' is required to ensure that vibrations eliminated as far as possible as this leads to errors in the scan data. Scans from platforms and bridges were avoided for this reason. For scanner setup, a Suunto compass was used to align the orientation of the scanner and a spirit level to ensure reasonable horizontal positioning, both helpful to facilitate scan alignment during the initial processing of data as it ensures that each scan is presented to the operator in the same orientation. Above ground, GNSS (Global Navigation Satellite System) is used to orientate the scanner instead, so these tools become optional. For scanning river channels, additional equipment such as haul bags, safety ropes and dry bags is necessary.

The LiDAR RiScan Pro scan processing software (Ullrich, 2017) was employed for the initial point cloud. The key feature of this software is its ability to perform multi-station-adjustment, MSA (Kennedy, 2013). Initial point cloud models were prepared in. LAS format.

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 92 |

Following initial data processing, the.LAS point clouds were imported into Hexagon 3-D Reshaper software (Landrivon, 2017). This permitted the development of surface models, which could be used for measurements, dissections and analyses. Final mesh models were prepared in STL formats so they could be analysed and processed by a wide range of software.

3.2 Photogrammetry

To ascertain the relationship of the cave to surface features, we used an unmanned airborne vehicle (UAV) or drone. Unfortunately, regarding the Cave Protection Act (Official Gazette of the Republic of Slovenia 2/2004), the team was not allowed to fly drone underground. A survey of the surface was performed both by LiDAR and drone throughout the collapse dolines (Velika and Mala dolina). The drone used was a DJI Phantom III drone with a 4K camera. Available free LiDAR data was not used at this stage as the point density was significantly lower than the level we could obtain with the LIDAR system employed. The drone derived surface model was used to confirm the orientation of the LiDAR point cloud data of the cave and produce some imagery. The limited vegetation in the dolines at the time of the survey did not obstruct or influence the derived surface model.

Flight paths were calculated and set up in the commercially available Dronedeploy (www.dronedeploy.com). The software directs the drone to take images at the required rate and with at least an 80 % overlap from the previous shot. A note of the GNSS location was collated with each image. The same software Dronedeploy also uses photogrammetry to stitch high-resolution photos together to create a 3D surface model.

3.3 Procedure - From Scanning to 3D Model

3.3.1 Scanner Setup

In order to ensure a stable, effective scan, a stable ground has to be found, and the tripod should be stabilised. The scanner has to be powered up, and scanning configuration checked. It defaults to the previous setup, so no new configuration is required unless any scanning requirement has changed. It is only necessary to select a new scanning position and start a scan. If any issues arose, a new scan is performed.

3.3.2 The Scanning Process

For 3D imaging and determination of cave dimension, the resolution for scanning density was set to 4 cm at 100 metres and the range parameter set to High Definition. In this mode, the scanner makes several measurements of each point and records the one returned with the most confidence. The whole cave is scanned station by station, by gradually moving through the cave. The entire view field was scanned (100 x 360°) at each station. The time required for each scan was 2 minutes, based on the scanner settings we required (4 cm spacing at 100 m). The scanner can scan at a much greater density if required. In the show cave areas, where the scanner could be carried safely between stations, generally, the time taken from starting one scan to starting the next was 8 minutes. In the wild cave, where obstacles necessitated packing the scanner up in its protective bags before moving, time varied between 12 to 25 minutes. Each scan recorded between 10 and 20 million points, lower where there is the sky or a lot of water, neither of which will reflect the laser beam to record a point.

3.3.3 Data Capture and Processing

All data is backed-up twice before any processing takes place. The Riegl GNSS system is accurate to 2-3 m and could be improved by integration with another more accurate device. Where the sky was visible, in the dolines, GNSSGNSS was recorded in WGS 1984 Global Coordinate System which is compatible with almost all GIS software. Like all surveying methods, surveying a closed loop improves accuracy, so stations are not sited just in line, but all around passages and chambers. However, this is not possible along the Hankejev kanal, where there is only one route by which the surveyors can move through the cave. Therefore, there will be some, albeit small, inaccuracy as to location.

3.3.4 Building a 3D Model

Once all the scans are uploaded into the software and a project created, it is necessary to align all the scans into a final point cloud model. The best option use is the default 'project co-ordinate system' supplied which places all the points onto a Cartesian coordinate system. These can be transformed onto a geographic system later. The Riscan software extracts data, using a Plane Patch Filter from which it can recognise common patterns across scans and thereby align scans almost automatically. Firstly, the scans need to be registered; this allows the software to create a set of references from which to align the scans, then the Plane Patch Filters created, followed by a manual rough alignment of the scans. Finally, the Riscan Pro software applies the Plane Patch filter patterns to automatically and accurately align the scans together. As there is so much data, it proved better to align scans one by one. Once aligned, the combined scans are filtered and combined into a single block of data called Polydata. The filtering allows for the setup of a common point spacing, such as 1 point per 25 cm², across the model. The initial model was then exported from the Polydata as .LAS point-cloud model.

The point cloud was then imported into 3D Reshaper (Landrivon, 2017). A mesh was created firstly by simply using the mesh commands, then using the "merge-common boundaries and fill holes" tools. The model was then refined from the original point cloud using the refine mesh commands and exported as a standard STL model.

Point cloud models created could be viewed and processed using free software such as CloudCompare (Daniel, 2016) and 3D models could be viewed using Meshlabs. Most of quality 3D software will allow viewing and processing of the LAS and STL file formats used.

Both the surface LiDAR scans and the photogrammetry are geo-referenced using onboard GNSS sensors. The accuracy of this is approximately 3–4 m, which was adequate for our needs. If ground control points had been used, that could improve to as low as 2 cm depending on the accuracy of the location of these points.

3.3.5 Volume calculations

Once a surface model of the cave is created in 3D Reshaper, in order to do volume calculations, all the holes in the surface must be filled. This is not as straightforward as there a many. This stems from not being able to position the scanner in every required position to scan every aspect of the cave. For example, due to the height of the river and the difficulty of negotiating the river at the river level. For instance, some areas of the walls below the path in the Hakejev kanal were not scanned. These holes must be filled

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 94 |

manually, but as long as no specific features are attempted to be represented, good knowledge of cave geometry and characteristics will permit a very good estimate in these areas. The holes where there are cave entrances must be filled as well, albeit just for this purpose. Once the mesh is closed, i. e. without holes, the properties of the surface model show its volume. It is a good idea to check that it makes sense by estimating rectangular blocks for each section of the cave and performing a manual calculation.

4 CAVE SCANNING AND RESULTS

4.1 Cave scanning

We scanned the caves in two campaigns. In 2018, the team captured the cave all the way from Ponor, through caves Mahorčičeva and Mariničeva jama, Mala and Velika dolina, to passage Šumeča jama and to the first part of Hankejev kanal (Hanke's Channel). We scanned as far as Swidovo razgledišče (Swida's viewpoint). The cave and surface were scanned from 320 stations.

Figure 3: Laser scanning of Hankejev kanal in 2018 (Photo M. Burkey).

In 2019 further 50 stations were scanned to the Martelova dvorana and 20 stations on the surface. The first report on scanning was published by Zupan Hajna and Walters (2019).

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 95 |

So far the 3D Scanning project of Škocjanske jame has been constructed via the use of 370 scanning stations, capturing 8.3 billion points and taking 2,600 hi resolution photos. It requires 250 GBytes of storage. If we include all the sub-models, videos and extractions, the overall storage requirement is almost 1Tbyte. In order to make use of the data, models were mostly decimated to at most one point per 0.1 m x 0.1 m surface area. The decimation is carried out with RiScan Pro, where an Octree Filter is applied to the data. This density is an aim, if due the range of the target surface, this cannot be obtained, in some areas, the density will be lower, though density is improved by multiple scans of the surface from different scanning stations. The compiled data compressed to a 3 GB shared memory with 48 million pixelspoints and then squeezed it to 8 million (8 MB) for ease of display. Such cloud of points can be viewed with different programs on personal computers; the example is 3D model of the cave produced in a Cloud Compare (Fig. 4).
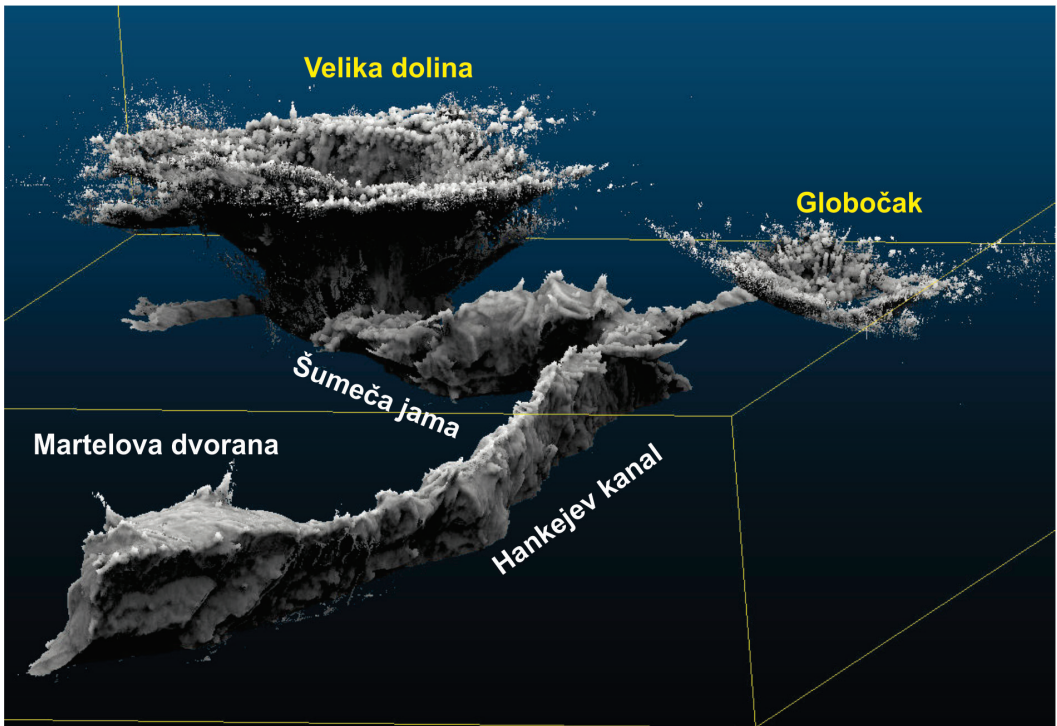

Figure 4: 3D point Cloud of Škocjanske jame made by CloudCompare; view from NW.

In addition, the scans show up details that are normally obscured by darkness and distance, as for instance speleogenetic features, that are too far away to be illuminated by available lights comment (Fig. 5).

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |
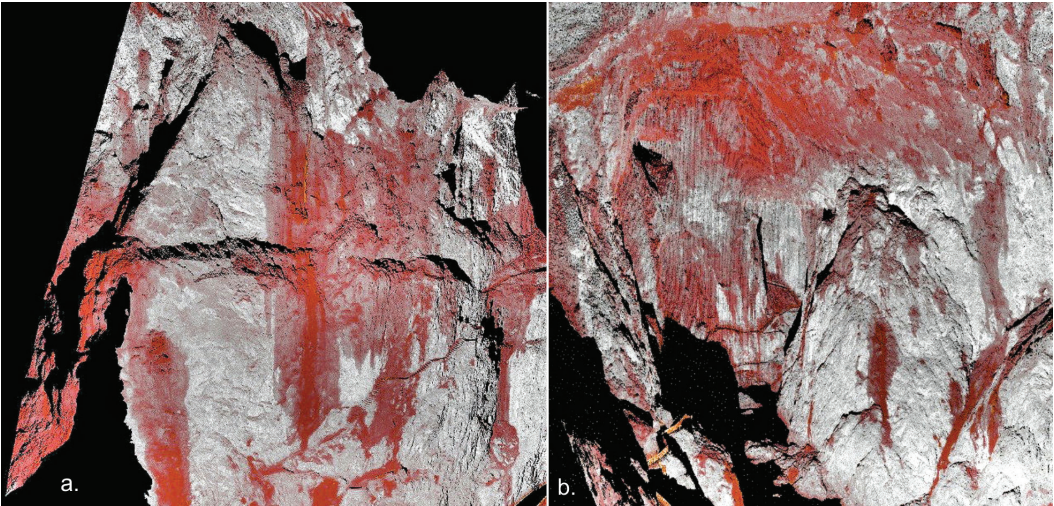
| 96 |

Figure 5: Wall features including pending wall failure fractures in Šumeča jama seen from the Point Cloud. The colour stems from difference reflectance levels of the cave walls

In the main cave detailed scans were taken of Ponvice (Gours) and of sediment profile in Tiha jama. Ponvice (Fig. 6a) were scanned with higher resolution (resolution 0.01 m; las data = 80 MB). Due to Cave Regulations, scans from above the gours could not be done, so data from the base of many of the gours is missing (Fig. 6b). Consequently, their volumes could not be calculated.
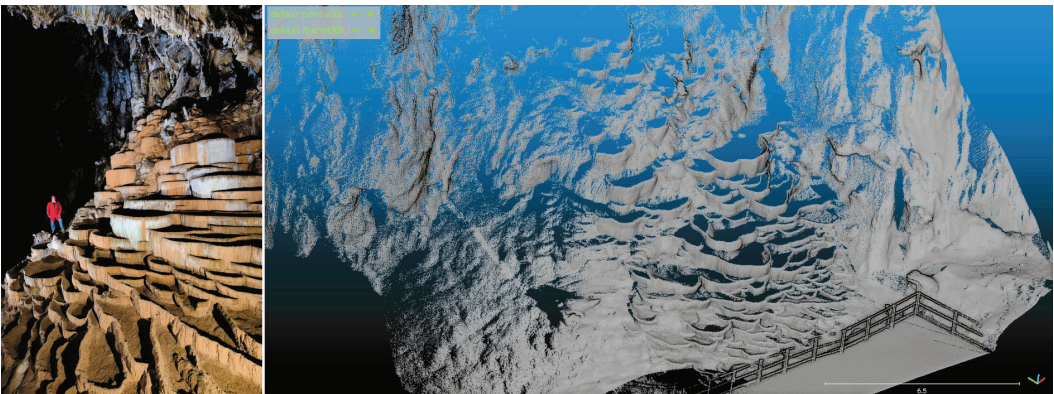
Figure 6: Comparison between the photo and 3D model of Ponvice: a.) photo (M. Burkey) and b.) CloudCompare 3D model.

4.2 Comparison with the caves' map

First, in our objectives was to compare the 3D model with the cave existing map (Drole, 2015). We extracted a ground plan of the Škocjanske jame made from tachymetric survey and the point cloud (on the image in grey) obtained by 3D laser scanning in February 2018. The layouts coincide very well, which reinforces the accuracy of both methods (Fig. 7).

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |
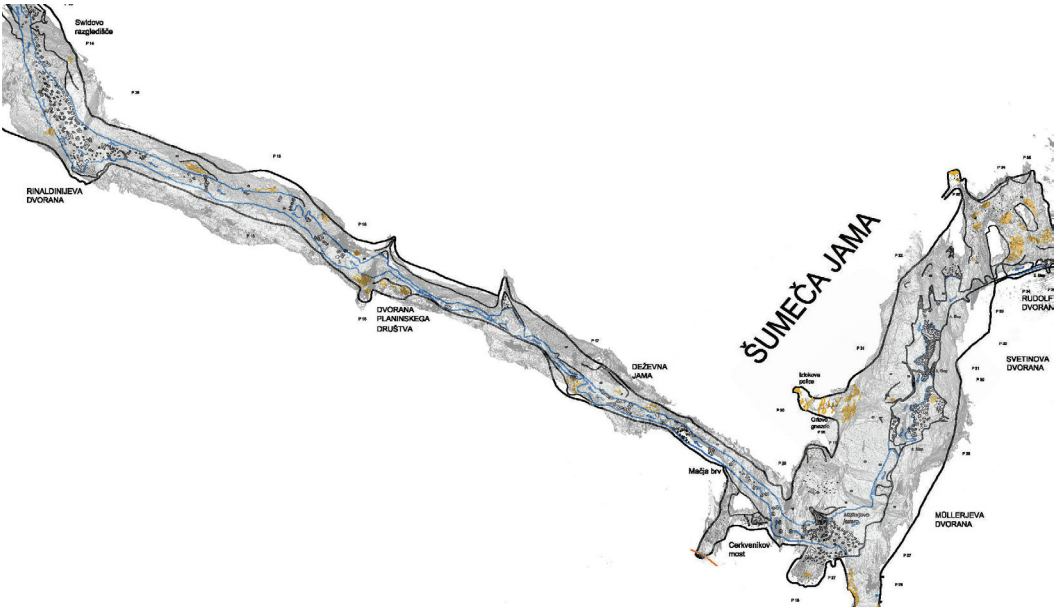
| 97 |

Figure 7: Comparison between the part of the ground plan (Drole, 2015) of the cave passages made from the tachymetric survey (black line) and the point cloud obtained by terrestrial laser scanning in February 2018 (points in grey).

4.3 Measurements and volumes calculation

Almost the whole cave was laser scanned. There are some small side passages, the passages in the continuation of Martelova dvorana and two new passages above it, which we didn't scan.

Figure 8: Laser scanning of Martelova dvorana in 2019 (Photo M. Burkey).

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 98 |

Overall cave volume from the ponor in collapse doline Velika dolina to Martelova dvorana is 6.13 million m³. Martelova dvorana (Fig. 8): chamber volume is 2.55 million m³; max. length is 314 m, width 143 m and height 158 m.

4.4 Surface scans

The rims of the collapse dolines Velika and Mala dolina, ponor of the river Reka and entrance to the pit Okroglica were scanned by TLS. The number of surface scans increasing from 12 in 2018 to 20 in 2019. Three points were tied into GNSS locations fixed by the survey undertaken by Drole (1997).
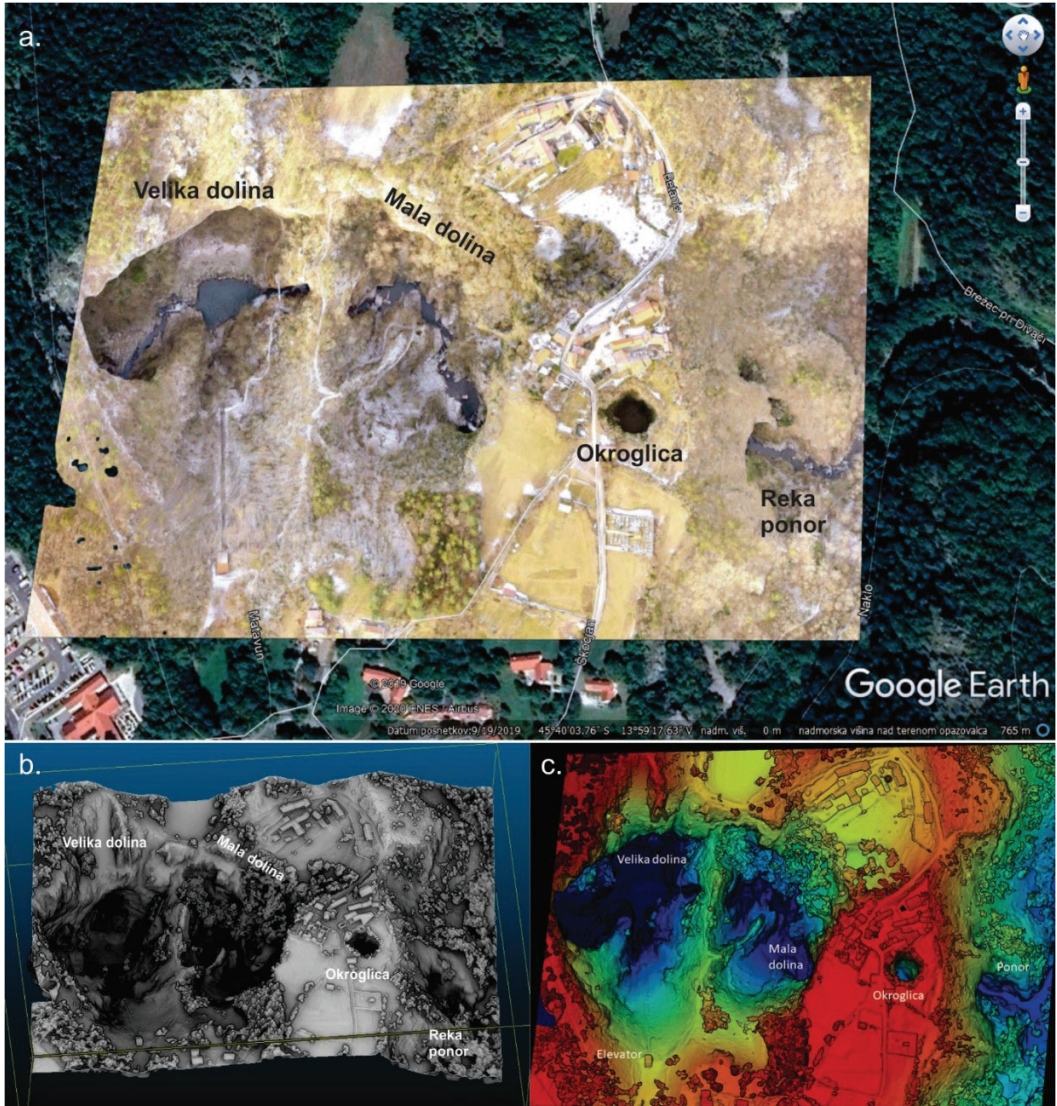

Figure 9: Examples of models obtained from UAV high-resolution images using photogrammetry: a.) drone image of collapse dolines layered on the Google Earth file; and their 3D models b.) in grey and c.) surface coloured regarding altitude a.s.l.

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 99 |

In addition to TLS a drone captured a large number of high-resolution photos over the karst landscape around the same collapse dolines (Figs. 9). The pictures were uploaded to Dronedeploy which, via knowledge of the location and orientation of each shot, recognising the same features in multiple shots photogrammetric procedures, built these images into a 3D surface model.

The accuracy of photogrammetric 3D model is 3-4 m. By using photogrammetry, a high-resolution 3D model, that contains elevation/height information (Fig. 9c), texture, shape, and colour for every point on the map, was created.

The models were combined in 3D Reshaper by selected known and predetermined reference points in both models and allowing the software to align them (Fig. 10).
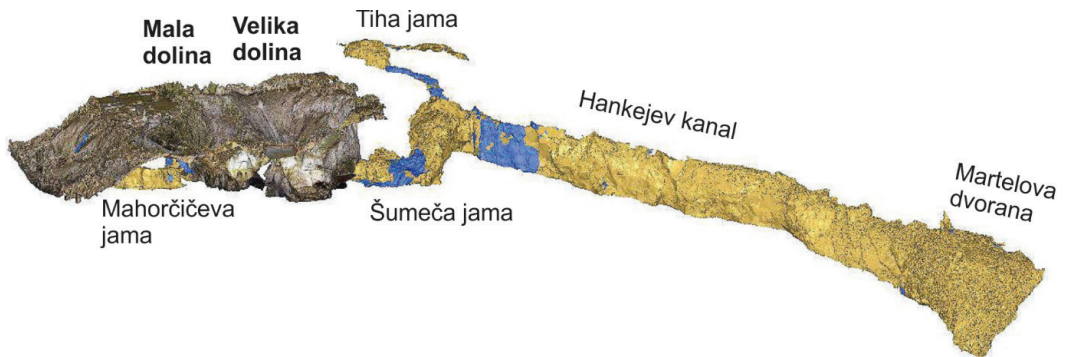

Figure 10: By 3D Reshaper's connected digital surface model around collapse dolines and 3D cave model.

5 DISCUSSION

5.1 Comparisons

Our measurements and calculations of the volumes are comparable with the data of the Institute from the 1990s. Volume of the whole cave we scanned is 6.13 million m³; Institute calculation was V = 5 million m³ (Drole, 1997). The volume of Martelova dvorana was calculated to 2.55 million m3, which was found to be a little larger than previously estimated (2.2×10^6 m³; Drole, 1997). There was a comparison done between maps produced by theodolite measurement and 3D laser scan; interesting was that there were no major differences in the layout of the two plans. We would like to emphasize that the cloud of points was only approximately placed on the existing map since 3D scanning data was still not attached to the tachymetric survey via GNSS points on the surface. The scanned point cloud extends beyond the cave plan at Reka ponor and on the margins of collapsed dolines the Mala and the Velika dolina, because the surface was also scanned but not mapped. The improvements in completeness of the TLS models must be taken as a reflection of improving technology and method and no so as to offer criticism of previous work which stand as excellent examples of work. It is not claimed that linear measurements using LiDAR will be better than those using tachimetry, far from it, however, the LiDAR does remove errors in the cartographer's estimations when drawing up a map based on just theodolite data.

Comparison with the largest chambers of the world measured until 2019 has shown that the size of the Martelova dvorana reaches the 11th place in the world (see Table 1) and 2nd in Europe after Salle de la Verna (3.6 million m³). Nevertheless, Martelova dvorana is the largest river passage in Europe.

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 100 |

Table 1:   As of December 2019.

No	Name	Cave	Vol (x10⁶m³)	(x10³m²)	Country	Area
1	Miao Room	Gebihe	10.59	151.99	China	Ziyun County, Guizhou
2	Sarawak Chamber	Nasib Bagus	9.81	168.87	Malaysia	Mulu National Park, Sarawak
3	Cloud Ladder Hall	Quankou Dong	6.23	56.74	China	Tongzi, Wulong County, Chongqing
4	Funnel of Light	Maoqidong	6.13	39.85	China	Leye County, Guangxi
5	La Muneca Fea	Tlamanictli-TZ1	5.90	65.06	Mexico	Tepepan, Zaragosa, Puelba
6	Hong Meigui	Niu Ping Dong	5.56	62.70	China	Leye County, Guangxi
7	Ghar-e-Dosar	Ghar-e-Dosar	4.33	79.14	Iran	Mehrib, Yadz
8	Majlis al Jinn	Majlis al Jinn	4.11	59.41	Oman	Selma Plateau
9	Salle de la Verna	Reseau de la Pierre San Martin	3.65	43.15	France	Sainte-Engrace, Pyrénées-Atlantiques
10	Api Chamber	Whiterock Clearwater System	2.89	42.73	Malaysia	Mulu National Park, Sarawak
11	**Martelova dvorana (Martel's Chamber)**	**Škocjanske jame**	**2.55**	**32.89**	**Slovenia**	**Divača, Kras**
12	Titan Chamber	Ban Dong Xinu - Chu Yan Dong	2.43	52.81	China	Doshan, Anlong County, Guizhou
13	Gran Sala GEV	Torca de la Carlista	2.14	84.31	Spain	Cantabria
14	Haiting Chamber (Left)	Nongletiankeng	2.12	40.53	China	Fengshun County
15	Marco Polo	Nongluidong	1.44	45.69	China	Dinlong, Jinya, Fengshan District, Guangxi
16	The Big Room	Carlsbad Caverns	0.93	45.36	USA	New Mexico
17	Haiting Chamber (Right)	Nongletiankeng	0.87	32.98	China	Fengshun County
18	Belize Chamber	Chiquibul Cave	0.81	46.38	Belize	Chiquibul

5.2 Problems in laser scanning of natural caves

Scanning the natural caves with heavy equipment is not easy, especially in the narrow, vertical or big and long cave passages. Most of 3D models of the caves were done in small ones or they scanned just one of the cave chambers for the scientific or monitoring purposes (*e.g.* Canevese, Tedeschi and Forti, 2009; Grussenmeyer *et al.,* 2010; Lerma *et al.*, 2010; Milius and Petters, 2012; Silvestre *et al.*, 2015; Oludare Idrees and Pradhan, 2016).

The biggest issues in large caves scanning are listed and described here.

1. Scientific Rigour: The discipline required to maintain surveying standards when cavers are getting cold, tired and hungry; scanning in manageable sections is important.
2. Shadows: Large speleothems, people, corners all create shadows. It is always necessary to perform many more scans than might have been perceived so as to capture all elements of the cave. That said, without special climbing and caving skills, some areas will always prove impossible to scan.

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 101 |

3. Colour: It is virtually impossible to scan in colour in large caves. Even the best light sources will not reach much beyond 50 m. So the furthest points will always be coloured black. To some degree this can be overcome by other scans that are closer to the subject, but obtaining perfect colour capture is very time-consuming work, matched with the unconvincing case for requiring colour data.

4. Errors: Measurement errors are small, especially if the scans are taken around a chamber so that, in effect a closed loop is obtained. However, in long passages where no loop closure is possible, errors will eventually become significant.

5. GNSS: When scanning where GNSS is available, The Reigl and indeed, all scanners' GNSS performance is limited but can be improved with integration with other specialist GNSS systems. Good software will allow corrections to be incorporated by adding the third party measured GNSS located fixed tie points into the scan registration process.

6. Range: Scanning at long range should only be undertaken where it is not necessary. The errors at long range become significant and result in errors in the model such as dual surfaces and repeated cracks and faults – both where there is only one in reality. This is largely overcome by discarding all points over 50 m in range in the scan registration process. For some scans, they will have to be kept.

7. ADD mixed pixels which can be particularly problematic when dealing with longer distances and a high surface details.

8. Cost: 3D scanning is a hideously expensive process, both in initial outlay, maintenance and the time required to process data. Here it has to be said that the price is correlated to the user requirements. The theodolite measurements might be cheaper, but do not provide so much cartographic detail as laser scanning.

6 CONCLUSION

During fieldwork, almost all the passages of Škocjanske jame and the slopes of the collapse dolines Velika and Mala dolina were scanned by TLS method. From the measurements and calculations of their volumes, it can be concluded that caves Škocjanske jame contain the largest known river canyon in Europe, that the Martelova dvorana is most definitely a chamber and is the 2nd largest in Europe and the 11th largest in the world (see the results as of November 2019 in Table 1). Furthermore, we can point out that 3D scanning will become a vital tool for the future study of caves.

In conclusion, we can say, that there is much scientific work still in progress reviewing this data, but reviews of speleogenesis, the role of freeze-frost in enlarging cave passage and the relationship between other caves in the Reka 'system' are underway.

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 102 |

Literature and references:

Boegan, E. (1938). Il Timavo. Studio sull'idrografia carsica subaerea e sotterranea. Memorie dell'Istituto Italiano di Speleologia, II, 251, Trieste.

Canevese, E. P., Tedeschi, R., Forti, P. (2009). The caves of Naica: laser scanning in extreme underground environments. The American Surveyor 6 (2), 8–19.

Daniel, G. (2016). CloudCompare. Retrieved Jan 21, 2018, from Cloudcompare: http://www.danielgm.net/cc.

Drole, F. (1997). New survey of Škocjanske jame. Proceedings of the 12th International Congress of Speleology, 6, 25–28. Basel: La Chaux-de-Fonds, Switzerland.

Drole, F. (2015). Digitalized map of Škocjan Caves. Archives of Karst Research Institute ZRC SAZU.

Grussenmeyer, P., Landes, T., Alby, E., Carozza, L. (2010). High resolution 3D recording and modelling of the Bronze Age Cave "Les Fraux" in Perigord (France). International Archives of Photogrammetry, Remote Sensing and Spatial Information Science, 38 (5), 262–267.

Kennedy, C. (2013). Riegl RiScan Pro - MSA Adjustment using Plane Patch Filter. https://www.youtube.com/watch?v=MDnqP5KV5eA, accessed 20. 1. 2018.

Landrivon, N. (2017). 3D Reshaper. https://www.3dreshaper.com/en/, accessed 21. 1. 2018.

Lerma, J. L., Navarro, S., Cabrelles, M., Villaverde, V. (2019). Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Parpalló as a case study. Journal of Archaeological Science, 37 (3), 499–507. DOI: https://doi.org/10.1016/j.jas.2009.10.011

Meeraus, A. (1913). Grotten und Höhlen von St. Canzian bei Divača (Triest) aus Zeitschrift des Deutschen und Oesterreichischen Alpenvereins 1890, Band 2.

Mihevc, A. (1994). The Martel's Chamber in Škocjanske jame. Acta Carsologica, 23, 205–214.

Mihevc, A. (1995). Nove meritve Martelove dvorane v Škocjanskih jamah. Naše jame, 37, 39–44.

Mihevc, A. (1998). Škocjanske jame – A contribution to Speleogenesis. Naše jame, 40, 11–27.

Milius J., Petters C. (2012). Eisriesenwelt – From Laser Scanning to Photo-Realistic 3D Model In Jekel T., Car A., Strobl J. & Griesebner G. (Eds.), GI-Forum 2012: Geovisualization, Society and Learning. Salzburg: 513–523.

National Geographic (2014). Amazing 3-D tour of a Chinese supercave. National Geographics. http://video.nationalgeographic.com/video/magazine/ngm-china-caves-3d, accessed 5. 9. 2019.

Novaković, G., Mlekuž, D., Rozman, L., Lazar, A., Peric, B., Cerkvenik, R., Peternelj, K., Erič, M. (2014). New approaches to understanding the world natural and cultural heritage by using 3D technology: UNESCO's Škocjan Caves, Slovenia. International Journal of Heritage in the Digital Era, 3 (4), 629-641. DOI: https://doi.org/10.1260/2047-4970.3.4.629

Oludare Idrees, M., Pradhan, B. (2016). A decade of modern cave surveying with terrestrial laser scanning: a review of sensors, method and application development. International Journal of Speleology, 45 (1), 71–88. DOI: https://doi.org/10.5038/1827-806X.45.1.1923

Silvestre, I., Rodrigues, J.I., Figueiredo, M., Veiga-Pires, C. (2015). High-resolution digital 3D models of Algar de Penico Chamber: limitations, challenges, and potential. International Journal of Speleology, 44 (1), 25–35. DOI: https://doi.org/10.5038/1827-806X.44.1.3

Ullrich, A. (2017). Riscan Pro, 2.6. http://www.riegl.com/products/software-packages/riscan-pro/, accessed 20. 1. 2018.

Official Gazette of the Republic of Slovenia No 2/2004. Zakon o varstvu podzemnih jam [Cave Protection Act].

Walters, R. (2016). Les plus grandes cavernes du monde en 3D, 48–51. Spelunca, 5 (142), 48–51. DOI: https://doi.org/10.3406/estat.1974.1783

Walters, R. (2017). Largest Cave Chambers in the World - 3D Scanning Project. UIS Bulletin, 59 (2), 52–53.

Zupan Hajna, N., Walters, R. (2019). Teretstično 3D lasersko skeniranje Škocjanskih jam. In Rožič, B. Geološki zbornik, 25, 158–163. 24. Posvetovanje slovenskih geologov.

Richard Walters
Commendium LTD
1a Hobson Court, Gillan Way, Penrith CA11, Great Britain
e-mail: richard.walters@commendium.com

Assoc. Prof. Dr. Nadja Zupan Hajna
Karst Research Institute ZRC SAZU
Titov trg 2, SI-6230 Postojna, Slovenia
e.mail: zupan@zrc-sazu.si

Richard Walters, Nadja Zupan Hajna | 3D-LASERSKO SKENIRANJE NARAVNIH JAM: PRIMER ŠKOCJANSKIH JAM | 3D LASER SCANNING OF THE NATURAL CAVES: EXAMPLE OF ŠKOCJANSKE JAME | 89-103 |

| 103 |