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Terrestrial Laser Scanning for the Visualization of a Complex Dome in an Extreme Alpine Cave System

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Summary: The 3D surveying of two big cavities with very complex shapes in the Dachstein Southface Cave, Styria, Austria, serves as an example to demonstrate the efficiency of exact coordinate registration in caves by means of laser scanning. The surveyed cave is not open to the public and classified as difficult. The complicacy of a suggestive visualisation of such complex cavities is shown using the so-called Ramsau Dome as an example. Digital animations are considered the only possibility to adequately visualise such cave systems. During a surveying campaign of several days the Riegl Z-420i laser scanner worked reliably as data acquisition instrument despite the extreme conditions regarding temperature, air humidity and dirt. The generated point cloud models represent the presently best data bases for application modelling like for well discharges in karst hydrology and photo-realistic visualisations.

Zusammenfassung: *Terrestrisches Laserscanning zur Visualisierung eines komplexen Hohlraums in einem extremen alpinen Höhlensystem.* Am Beispiel der Vermessung von zwei mächtigen und formmäßig komplexen Hohlräumen in der Dachsteinsüdwandhöhle, Steiermark, Österreich, wird das Potential für deren Formerfassung mittels Laser-Scanner erläutert. Die Höhle ist nicht für die Öffentlichkeit zugänglich und gilt als schwer begehbar. Anhand des so genannten Ramsauer Doms wird die sehr schwierige graphische Darstellung solch komplexer Hohlräume demonstriert und als einzige Möglichkeit für eine adäquate Visualisierung die digitale Animation erkannt. Der eingesetzte Laser-Scanner Riegl LMS Z420i hat sich unter extremen Bedingungen hinsichtlich Temperatur, Luftfeuchtigkeit und Schmutz während des mehrtägigen Einsatzes als Datenerfassungsinstrument bewährt. Die letztendlich entstandenen Punktwolkenmodelle stellen die bislang besten Datengrundlagen für verschiedene Applikationsmodellierungen, wie z. B. für Quellschüttungen in der Karsthydrologie und fotorealistische Visualisierungen, dar.

1 Motivation and Location

Being the most valuable resource of the 21st century, water – and in particular potable water – is gaining increasing importance, also in research. In the Alps and world-wide the calcareous karst mountains are the main bearers of underground water. Therefore it is certainly of high interest for karst hydrologists and, hence, speleologists to obtain detailed information about shape and volume of the cavities inside the limestone mountain ranges. This allows to get a grip onto their water storage capacity and to model both seepage/percolation and run-off.

Moreover, caves allow geologists and in particular structural geologists, to combine scarce and often vague surface evidences concerning the geological structure of mountains with explicit and indicative subterraneous observations to a clear(er) three-dimensional tectonic development model of the respective area. This applies especially to the Dachstein Massif where mighty layers of carbonatic rocks have been thrusted over the metamorphic clastites of the East-Alpine Greywacke Zone (Buchroithner 1993).

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Based on our present knowledge of the Dachstein South Face Cave (DSFC) the idea sounds both intriguing and plausible that deep in the mountain the cave might intersect along the aforementioned thrust-plane, thus allowing not only a visual inspection of this major tectonic feature of the Alps but also the possibility of quantitative subterraneous measurements.

A particular appeal and challenge for the exploration of the DSFC is the expectation that possibly the connexion between the DSFC and the complex cavity system of the Hierlatz Cave System on the northern side of the Dachstein Massif, which has already been proved by tracer experiments, may one day be crossable, i. e., climbable, by men. Such an extreme traverse under the whole massif of the Dachstein Mountains would then represent one of the most adventurous and hugest speleological enterprises in the world (cf. also statements by the first author formulated by Schön 2007a, 2007b).

Moreover, the application of modern 3D surveying techniques like 360° rotational laser scanning to very complex cave systems had been another challenge. Their outcome might be expected to serve the visualisation of the complex best. Hence, one of the major motivation aspects of another 3D cave surveying campaign (cf. Section 4) was the attempt to achieve adequate measurements for a close-to-nature optimised geovisualisation. Since different textures and colours do not play that big a role in this pure limestone cave, priority was given to the mere extraction of the cave shape, and no photographs were acquired simultaneously.

The entrance of the DSFC is located right below the prominent peak of Hoher Dachstein (2995 m), at 47° 28’ 00.85” N and 13° 36’ 31.92” E in a rock-wall called Mitterstein (cul-

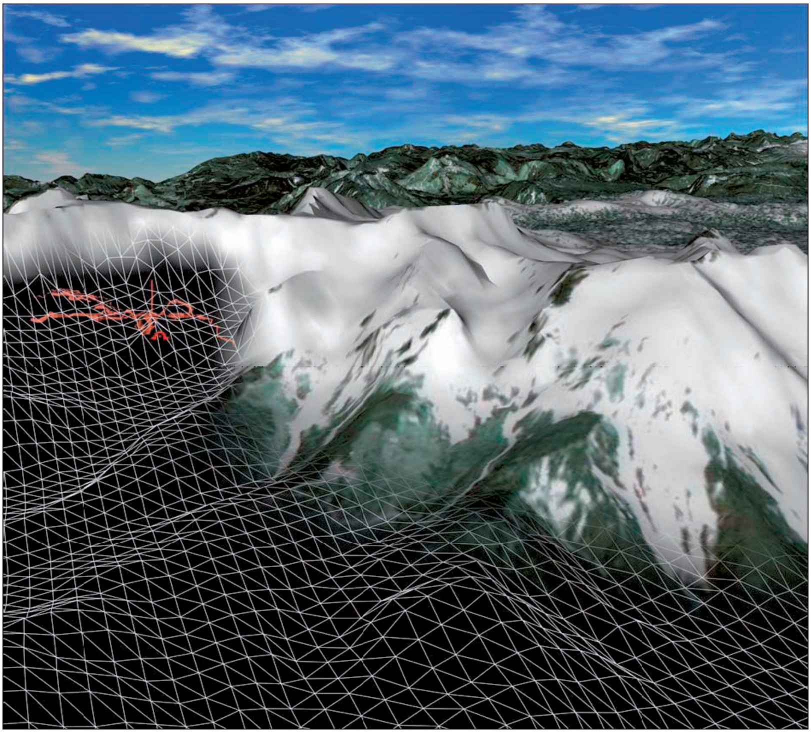

Fig. 1: Digital terrain model of the Dachstein Massif, view towards northwest, in the near range represented as a triangular network draped with a geo-coded Landsat TM imagery viewed against the Dead Mountain Range in the background. In the upper left corner the position of the Dachstein South Face Cave (DSFC) can be seen through the wireframe of the relief model. For location of cave entrance in map see Fig. 2. 4 mm left the Ramsau Dome.

minating at 2122 m) in 1834 m at the foot of the mighty, almost 900 m high and roughly 2900 m wide Dachstein South Face. It can only be reached by climbing. From the end of the curvy Dachstein Road at 1710 m a mountain trail, passing the Dachstein South Face Hut (1910 m), leads close to the Mitterstein rock face where a one-pitch rock climb allows to reach the cave entrance (cf. Fig. 1 and 2). The position of the "Dachstein Hole", as it is called by the local population, is illustrated in Fig. 1. The cave is indexed in the Austrian Cave Catalogue under Code No. 1543/28. Its explored extension under the Dachstein at the end of 2007 is shown in Fig. 2.

Due to the initiative and the repeated invitation of the Cave Research Group of the Schladming Chapter of the Austrian Alpine Club (OeAV), in 1996 (Graf 1996) the first author of this paper and a group of venturesome students from Dresden started a series of survey campaigns in the DSFC. Their intention was to obtain a three-dimensional cave model by conventional geodetic measurements. In order to achieve this, a traverse with frequent cross-sectional measurements has been surveyed, an undertaking of extreme hardness. This finally resulted in the Dresden proposal to test the advanced technique of rotational laser-scanning in order to survey some of the bigger halls in this complex cave system which is, moreover, comparatively difficult to climb.

2 Previous Surveys

Already in 1910, the Moravian speleologist Ing. Hermann Bock, his wife and companions set out from Graz and made a first survey of the outer parts of the DSFC, which was discovered by the Dachstein mountain guide Johann Knauß in 1886 and even earlier by local hunters, and published in 1913 a first simple sketch-map up the famous Ramsau Dome. One-hundred years later, in 1986, the Salzburg-based karst hydrologist W. Gadermayr and companions performed an uranine tracer experiment at a spring between Bivouac 2 and 3 and also produced a new map (Graf 1996). Based on these advance efforts in the same year a first surveying reconnaissance trip into the cave until close to Bivouac 3, i. e., behind the Schladming Dome, was carried out by Fritz Ebner, Mining University in Leoben, Austria, Anton Streicher, Vice Mayor of the City of Schladming and head of the Cave Research Group in Schladming, Austria, and the first author. The years 1996 to (spring of) 2007

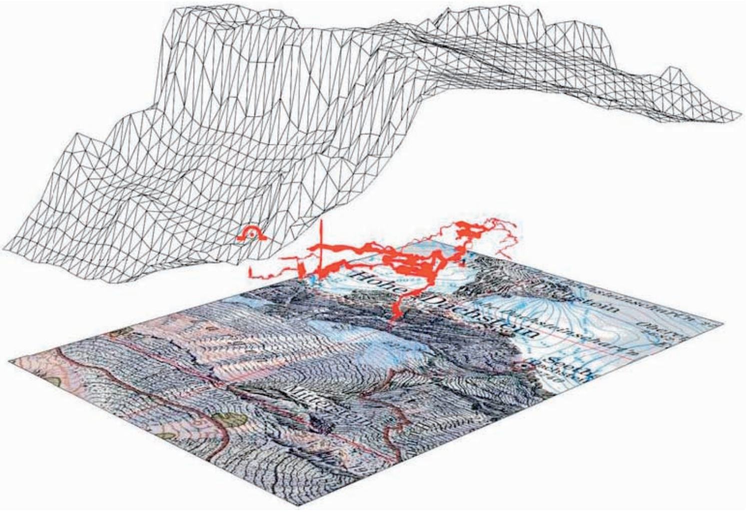

Fig. 2: Depiction of the complex system of the Dachstein South Face Cave (as explored until the end of 2006) in between a wireframe representation of the relief and a reproduction of a part of the 1 : 25 000 sheet "Dachstein" of the Alpenverein Map Series, Edition 2005. The vertical red spike represents the famous Schladming Shaft which reaches a height of at least 150 meters and which was also measured by laser scanner during the described campaign.

saw seven multi-day cave expeditions jointly performed by the Institute for Cartography of the Dresden University of Technology (TUD), the Cave Explorer Group from Landshut, Bavaria, and naturally the aforementioned cavers from Schladming. Within these years the DSFC was measured using traditional surveying-equipment, i. e., theodolite and suspension compass, in the manner described above (cf. Section 1). A short speleological history account by VHO (2008) is also accessible under www.hoehle.at/deutsch/SuedwandGeschichte.htm.

As an outcome of these operations, apart from a final internal surveying report of the Institute for Cartography of the Dresden University of Technology written by Graf (1998) and a comprehensive diploma thesis about the detailed 3D modeling and animated cartographic visualization of the – at that time surveyed parts of the – "Dachstein Hole" by Teichmann (1999), two popular-scientific educational films about the activities of the Dresden Group were published. These films of 18 and 36 minutes length respectively were several times on the programs of various TV channels, thus very well documenting the surveying methods used for the public. Using these methods, the measuring of extremely big cavities with adequate precision was rather unrealistic. To get a more detailed 3D-model of these halls the first author of this paper decided to make use of the advantages of laser-scanning.

3 Campaign Logistics

In the winter semester 2006/07 speleologists from Bad Mitterdorf in Styria, Austria, together with 8 cavers from Dresden undertook a big combined surveying campaign of 10 days under the leadership of Robert Seebacher, Bad Mitterdorf, and the first author. This enterprise which comprehended the surveying of both, the so-called Ramsau Dome and the Schladming Shaft, and an advance to the most distant parts of the cave system, some 8.7 km away from the entrance, required an intensive preparation and complex logistics. The latter ones included precursors to this event performed by both the Bad Mitterndorf and the Dresden speleology groups. Moreover, cartography students of the Dresden University of Technology were employed as porters for nutrition and gear along the small trail up to the cave entrance. Last but not least the laser scanner weighing some 16 kg incl. wrapping, the laptop, several smaller lead-acid batteries (cf. Section 4) and the tripod had to be carried into the cave – and finally back out!

The whole surveying campaign was realised under extreme circumstances regarding both the accessibility of and the rock-climbing difficulties in the cave: So the way back from the bottom of the Schladming Shaft, a near-vertical cavity of some 12 m in diameter and approx. 150 m in height requires about 60 m of jumar-ascending on a freely suspended rope. Moreover, constrictions barely wide enough to squeeze the laser scanner (cf. Figs. 2 + 3) through them had to be negotiated.

Thanks to the cooperation with the cavers from Schladming a nearly horizontal suspension rope-bridge of 9.4 m length (calculated using the Riegl RiPROFILE® post-processing software) had been installed in the Ramsau Dome in order to facilitate movement in this part of the DSFC (cf. Fig. 4, 6, and 9). Previ-

Fig. 3: At the lower end of the 60 m-rappel through the nearly vertical Schladming Shaft. Note the caving pack containing the 60 cm×40 cm×25 cm wrapping and the laser scanner which is all in all weighing approx. 16 kg.

ously, it had only been possible to proceed by rappelling 11.5 m to the base of the dome on one side and ascending the other one by difficult rock climbing. In any case, to reach the Schladming Shaft, first 17.3 m have to be climbed on a free-suspended rope by jumar-ascending. This is, above all, an interesting statement that corrects the passed-on overestimation of the cavers that you have to negotiate a vertical distance of 20 m plus. (All distances calculated using the Riegl RiPROFILE® software).

4 Laser Scanning

As already mentioned, it was unrealistic to measure the extremely large cavities inside the DSFC by using the described traditional methods. In order to get a more detailed 3D-model of these cavities the first author decided to use a Riegl LMS Z420i laser scanner (cf. Fig. 4). Its technical specifications can be obtained from the product information provided by Riegl Laser Measurement Systems. The whole system is battery-powered and easily portable, but yet robust and operable under a wide range of environmental conditions. Moreover, the decision to use this scanner instead of a phase difference scanner was triggered by the fact that the very model had already previously been successfully used for the scanning of open pits and constructed tunnels. Riegl Corp. also welcomes another test of their LMS Z420i under extreme conditions.

Despite the exceptional circumstances regarding temperature, air humidity, argillaceous dirt and dripping water, the instrument demonstrated in these harsh situations its outstanding qualities with respect to robustness and usability. Fig. 3 documents a typical climbing situation during the scanner transportation inside the cave, and Fig. 5 shows a picture taken during the work with the laser scanner in the Ramsau Dome.

The scanner can be manually tilted in 5-degree steps to guarantee a full 360°×360° field of view. Fig. 4 illustrates this and all the other features described in this paragraph (cf. Number 1 in Fig. 4). The system is complemented by a data acquisition system based on a standard laptop (3). Data acquisition, sensor configuration, data processing and storage are operated by the companion software RiSCAN PRO®. The scanner is mounted on a standard

Fig. 4: Operating the Riegl LMS Z420i at a rock pulpit in the Ramsau Dome. Location cf. Fig. 2. For explanation of the figure see text above.

surveying tripod (2), power supply can be realized by any power-resource between 12 and 28 voltage. Inside the cave special light-weighted battery-packs were used (4). The laptop was also running on these batteries. Recharging of the battery-packs was realized by using a generator-station located in the “base-camp” at the cave entrance.

Marked ground-control points already precisely measured in both directions (inbound and outbound) by measuring tape and analogue theodolite during previous campaigns were used to obtain the correct orientation of the point-cloud acquired by the scanner, within the global coordinates. Special fixing equipment was used to guarantee an exact position of the reflector targets. Despite the high humidity no difficulties occurred with the signal reflection.

Five 360° high-resolution scans with 12000 points were acquired on each side of the basal canyon (cf. Fig. 4, 6, and 9). In order to obtain near-realtime point-cloud visualisations of the measured surfaces – last not least for quality control and the detection of concealed spaces – Riegl software was used, too. The companion program systems RiSCAN PRO® and the post-processing tool RiPROFILE® enabled an automatic registration of the acquired point-clouds using a minimum of three but mostly four targets. This allows skipping the levelling of the scanner and the measuring of the scan-position to a degree of sub-minute accuracy. RiSCAN PRO® and RiPROFILE® automatically detected the targets because of their high reflectivity. Due to the complexity of their shape and the resulting occluded surface portions, in the Ramsau Dome as well as in the Schladming Shaft measurements at several scan positions and with different tilting angles at each position had to be carried out.

Using control points measured in a traditional geodetic way (accuracy some millimeters) each point cloud, acquired from different scan positions, was then automatically registered into the given global coordinate system. In a first step the global coordinates of the ground control points were imported as ASCII into RiSCAN PRO®. For each scan-position the scanner detects all visible ground control points because of the high reflectivity of the reflector targets. The highest possible resolution of the scanner guarantees a maximum precision and accuracy for the target measurements. The resulting coordinates are stored in the scanner’s own coordinate system. To register a scan position into global coordinates it is necessary to calculate the correct translation- and rotation matrix which was also done by means of the aforementioned software.

If a minimum number of only three targets is available, the matrix is calculated fully automatically by finding corresponding points between the scanner’s own coordinate system and the given global coordinates. The algorithm which is used to find the corresponding points compares all 3D distances between the targets. In this case the user can mount the scanner in any orientation. In principle the scanner can be also mounted over a ground-control point and leveled by means of the laser scanner’s inclination sensors. One visible target is enough to calculate the correct bearing angle. This workflow, called “backsighting orientation”, however, turned out to be not applicable under the narrow conditions inside the cave.

RiSCAN PRO® also allows registering the point-cloud of a certain scan position by just using overlapping scan areas of an already registered scan position. This workflow is not limited to two scan positions, it can be run on a number of different scan positions at the same time. The algorithm (the so-called ICP algorithm, Besl & McKay 1992) works iteratively and detects the closest point of the other point-clouds for each point in a point-cloud. The adjustment iteratively modifies position and orientation information of each scan position until the error reaches a minimum.

All these registration tasks deliver results of just a few millimeters of standard deviation. The overall accuracy (geo-reference) depends on the precision of the given ground control points (cf. above).

5 Visualization of Surveying Results and Derivates

After the registration at each scan station the primary output delivered is one combined point cloud for each of the surveyed huge cavities (halls, domes), representing a sampled

Fig. 5: Illustration of an ~ 200° sector of the point cloud of one single rotational laser scan showing the rock pulpit ("plateau") where (the former) Bivouac 1 is located below the rock face in the background (cf. Figs. 7–9). Note the rope of the suspension bridge (lower left) and another fixed rope obliquely leading some 25 m up the rock face to the cave tunnel which leads to the Schladming Shaft. Distance from viewing point to far range approx. 25 m.

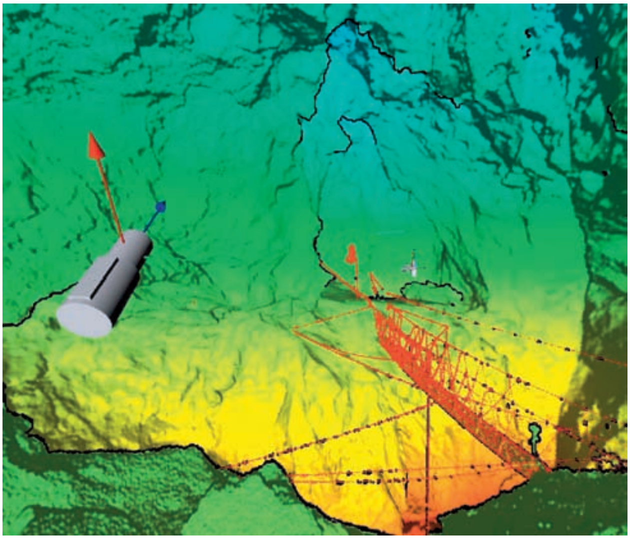

Fig. 6: Visualization of a portion of the point cloud of one scan of the Ramsau Dome as seen from near the measuring position with relief-shaded and color-coded visualization. Distance from the reddish near range, which corresponds more or less to the position of the laser scanner in the depicted scene, to the blue far range amounts to approx. 23.6 m. The RGB arrows indicate the orientation of the laser scanner at this scan position. Red lines correspond to the ropes of a suspension bridge erected for easier crossing of the basal canyon of the cavity.

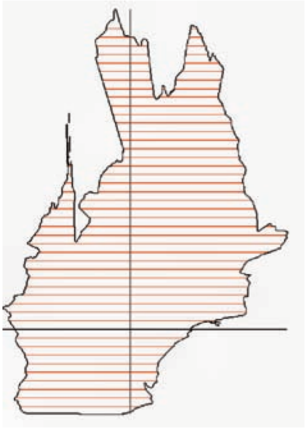

Fig. 7: East–West trending vertical cross-section through the Ramsau Dome showing 1 m contours in red. Black coordinate lines correspond to the vertical rotation axis of the different visualizations of the cavity and the internally defined "zero level" of the laser scanning campaign. The total height of this cavity amounts to 47 m (which cannot be displayed in one vertical section though). On the right is the rock pulpit of Bivouac 1 at a height of some 11 m above the bottom (cf. Figs. 4 + 8).

replica of the objects' surface (cf. Fig. 6). Triangulating the point-cloud results in a 3D surface model (cf. Figs. 6, 8, and 9), this model can then be used for further post-processing: volume calculation, contouring and horizontal as well as vertical and horizontal profiling (cf. Fig. 7) can easily be performed.

The total height of the dome is approx. 46.9 m, its maximum horizontal diameter 28.1 m. Its volume amounts to 325 m³. This calculation is based on the fact that some remaining uncovered patches of the irregular surface of the cavity have simply been closed by an approximating algorithm (see below). Hence, this figure represents a minimum value.

The impossibility to make extrapolations for surface portions not shown in the point clouds prevents to close holes subject to dead corners/blind spots by methods commonly used for geometrically well-defined objects in urban environments (e. g., Schnabel et al. 2006 cum lit.). Here, the use of methods based on Bézier splines like NURBS led to acceptable results. It has, however, to be kept in mind that – in contrast to anthropogenous objects – principally these interpolations represent solutions void of any proximity to reality. In any case, the closed point cloud models outweigh by far

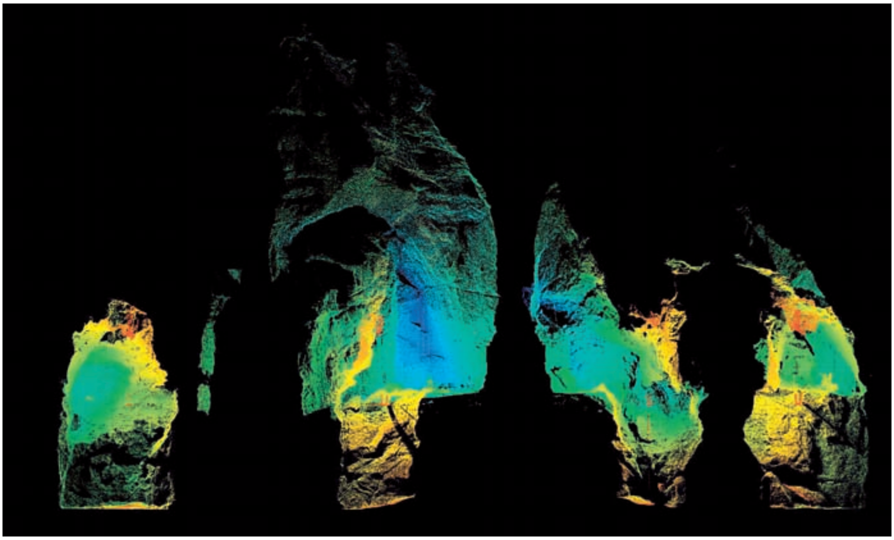

Fig. 8: The individual figures show color-coded views from 4 different directions into the slit cavity of the Ramsau Dome. Apart from animated visualizations, possibly such multiple illustrations represent the best possible way of conveying an impression of the complex shapes of such cave domes. Spectral color-coding in this and the following figure is not to scale but adjusted to the respective maximum range.

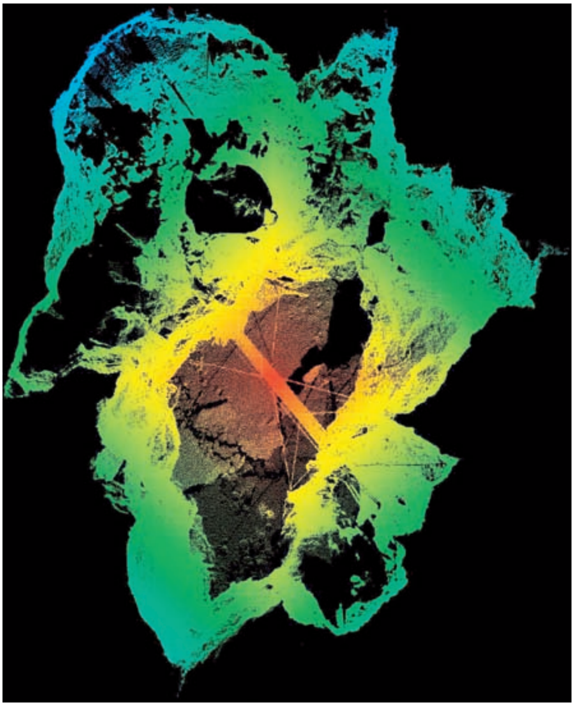

Fig. 9: Top-down view (radial color-coding from central axis into the Ramsau Dome). The suspended 9.4 m long rope bridge over the basal canyon with its wirings can be clearly seen.

the previous results made with bump-mapping techniques draped on TIN models which were generated by the "classical" surveying methods described above (cf. Teichmann 1999).

Comparisons between laser distometer measurements of the distances between polygon points of previous surveys and the corresponding distances acquired during the laser scanning campaign showed practically no deviation, i. e., less than 2 cm. The absolute elevation of the afore mentioned suspended rope-bridge in the Ramsau Dome amounts to 1780.4 m asl (WGS84). This statement is possible due to the fact that the interior measurements within the DSFC were linked to previously surveyed points tied to the National Geodetic Network of Austria. It corroborates the previously made relative vertical measurements, which indicate a 60 m descent from the cave entrance.

6 Assessment of Results

Until present time laser scanning has been frequently used for the three-dimensional surface documentation of cultural heritages of different size such as architectural, archaeological or natural ones (cf. Herdt & Jones 2008, Pettitt et al. 2007, Birch 2008, www.stonepages.com/ news/archives/ 000757.html, Kersten et al. 2009, Nothegger & Dorninger 2009).

Caves have mainly been surveyed by 3D laser scanning if their access and their "walkability" were comparatively easy (cf. Fryer et al. 2008, www.high-pasture-cave.org/index.php/news/comments/ 168/), as it is usually the case with caves affiliated to mines (which are mostly easily accessible; cf. the Cueva de los Cristales near Naica, Mexico, a site connected to mining shafts; www.faro.com/ content.aspx?ct=ge&content=news&item=14; Canevese et al. 2008) and with natural tourist caves which are open to the public. Actual "research caves" which are only climbable for speleologists have, so far, only rarely been surveyed by means of laser-scanners. To the authors' knowledge, the second-largest cave chamber in the world at Majlis Al Jinn in Oman has been surveyed using a laser scanner. This hall, however, is "easily" accessable by "simple" rappelling over a distance of 150 meters (www.youtube.com/watch?v=QgDHTDQp8Q0). There, neither creeping through super-narrow bottlenecks nor climbing is required. Also in terms of visualisation of complex natural caves, so far almost exclusively simplified box-shape representations have been published (cf. www.esri.com/industries/cavekarst/graphics/karst_ro_bg.jpg).

Hence, the surveying reported in this paper to some degree represents a premiere. Certainly, the transportation of a terrestrial laser scanner of the quality and weight of the Riegl LMS Z420i both through a bottleneck which was barely big enough to squeeze the laser scanner through and over a freely suspended 60 m rappel-and-ascend pitch with dripping water is a rather unique undertaking.

7 Conclusions and Outlook

In conclusion, the described cave surveying campaign, which was from its beginning meant to serve as a test operation, well demonstrated the feasibility of the used methodology and also of the utilised laser scanning device for the three-dimensional measuring of complex irregular cavities of medium to large size (up to several tens of meters) with frequent dead spots. The instrument, according to the producer's fact sheet dust- and splash-water-proof, turned out to be also reasonably "mud- proof".

Future operations of this type will – personnel with adequate scientific and technical background ***and*** alpinistic and speleological skills provided – certainly be able to serve both the purpose of solving tectonic underground conditions and of quantifying the shapes and volumes of subterraneous cavities. This, again, allows to acquire information about the genesis of particular karst caves and to come closer to a quantitative model of karst-water behaviour, and thus to better estimates of the "porosity" and storage volume of limestone massifs, and hence possible discharge rates of karst wells.

With respect to a visualisation which allows the viewer of "flat" (i. e., non-autostereoscopic) depictions to obtain a realistic conception of the respective complex cavities, however, one has to state that the only means providing an adequate picture of the shapes is a digital animation. Even a series of different cross-sections and colour-coded oblique views from different directions (see above, in particular Fig. 10) cannot be sufficiently suggestive of the physical shape. In this respect electronic visualisation means are clearly superior to hardcopy displays. At this point the animation of the High Pasture Cave published by Birch (2008) in the digital version of *Past Horizons* has to be seen as one of, if not *the* first reasonable example.

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References

Besl, P. & McKay, N., 1992: A method for Registration of 3-D Shapes. – IEEE Transactions on Pattern Analysis and Machine Intelligence **14** (2): 239–256.

Birch, S., 2008: Excavations at High Pasture Cave, Isle of Skye. – Past Horizons (electronic version), **5/2008:** 28–31.

Birch, S., 2008: Laser Scanning at High Pasture Cave. – www.high-pasture-cave.org/index.php/news/comments/168/ [30 December 2008].

Buchroithner, M.F., 1993: Korallenriffe und Gletscherströme. Zur geologischen Entwicklung des Dachsteins. – Alpenvereinsjahrbuch "Berg 93" **117:** 61–74.

Canavese, E.P., Tedeschi, R. & Forti, P., 2008: Scanning the Caves of Naica in Mexico. Laser Scanning Technology in Extreme Environments. – GEOInformatics (electronic version), December 2008: 6–9.

The Courier, 2004: 3D laser scanning of the Wemyss caves. – www.stonepages.com/news/archives/000757.html [last access: 30 December 2008].

Fryer, J.G., Chandler, J.H. & El-Hakim, S.F., 2008: Recording and Modelling an Aboriginal Cave Painting: With or without Laser-Scanning? – ISPRS Proc. 3D Archaeology, 8 p., CD-ROM., www.commission5.isprs.org/3darch05/pdf/3.pdf.

Graf, M., 1996: Exkursionsbericht zur Fahrt der Landshuter Höhlenforscher nach Schladming, Steiermark, Österreich, vom Donnerstag, den 21.3.1996, bis Dienstag, den 26.3.1996. – Internal Report, Institute for Cartography, Dresden University of Technology.

Graf, M., 1998: Exkursionsbericht zur Film- und Sondierungsforschung der Höfos Landshut gemeinsam mit der ÖAV-Höhlengruppe Schladming und der TU Dresden vom Mittwoch, den 17.6.98, bis Sonntag, 21.6.98. – Internal Report, Institute for Cartography, Dresden University of Technology.

Herdt, G. & Jones, M.W., 2008: Scanning Ancient Building Components. – Photogrammetrie – Fernerkundung – Geoinformation **4/2008:** 245–251.

Kersten, T.P., Lindstaedt, M. & Vogt, B., 2009: Preserve the Past for the Future – Terrestrial Laser Scanning for the Documentation Analysis of Easter Island's Moai. – Photogrammetrie – Fernerkundung – Geoinformation **1/2009:** 79–90.

Nothegger, C. & Dorninger, P., 2009: Filtering of High-Resolution Terrestrial Laser Scaanner Point Clouds for Cultural Heritage Documentation. – Photogrammetrie – Fernerkundung – Geoinformation **1/2009:** 53–64.

Pettitt, P., Bahn, P.G. & Ripoll, S., 2007: Palaeolithic Cave Art at Creswell Crags in European Context. – Oxford University Press.

Schnabel, R., Wahl, R. & Klein, R., 2006: Shape Detection in Point Clouds. – *Technical Report CG-2006-2*, Universität Bonn.

Schön, St., 2007a: Mit dem Laser im Labyrinth. – Sächsische Zeitung, March 24/25, 2007: M2.

Schön, St., 2007b: Vorstoß ins Dachstein-Massiv. – National Geographic Magazine Deutschland, April 2007: 42–49.

Teichmann, D., 1999: Großmaßstäbige 3D-Modellierung und animierte kartographische Visualisierung der Dachstein-Südwandhöhle, Steiermark (Österreich). – Unpubl. Diploma Thesis, Institute for Cartography, Dresden University of Technology.

Verein für Höhlenkunde in Obersteier (VHO), 2008: Geschichte der Südwandhöhle (Dachsteinloch) – www.hoehle.at/deutsch/SuedwandGeschichte.htm [30 December 2008].

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