Detection of Divaška Jama corridors behind (to the SW) Trhlovca cave using low frequency high power ground penetrating radar

Article in Acta Carsologica / Kansoslovni Zbornik · September 2018
DOI: 10.3986/ac.v47i2-3.5187

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DETECTION OF DIVAŠKA JAMA CORRIDORS BEHIND (TO THE SW) TRHLOVCA CAVE USING LOW FREQUENCY HIGH POWER GROUND PENETRATING RADAR

DOLOČITEV ROVOV DIVAŠKE JAME V JZ SMERI ZA TRHLOVCO Z UPORABO ZELO MOČNEGA NIZKOFREKVENČNEGA GEORADARJA

Pavel KALENDA¹, *, Rudolf TENGLER², Stanka ŠEBELA³, Matej BLATNIK³ & Andrej GOSAR⁴

Abstract

Ground penetrating radar (GPR) named “Roteg” was used to detect known and unknown passages of Divaška Jama and Trhlovca caves in SW Slovenia. “Roteg’s” main characteristics are an extraordinary high power output (20 MW) and high voltage on antennas (up to 20 kV), which allows penetration more than ten times deeper than common GPRs. During the measurement we used 3-m long antennas (50 MHz) with a central frequency of 50 MHz and we clearly detected the reflections from the depth of 200 m after data processing. During field survey 22 profiles were completed with a total length of 4487.97 m. Pretnerjeva and Žibernova Dvorana chambers in Divaška Jama were well visible on radarograms. New big cavities, which were detected below profiles P18, P21 and P22, are almost all at the same level of 350 – 400 m a.s.l. There is another group of cavities at a level of 420 – 450 m a.s.l., which corresponds to Trhlovca. Both cave groups are separated by the gap which extends in the vertical direction, and probably presents a tectonic zone, which is as well visible on the radarograms. By the use of “Roteg” at the karst surface we were able to detect known caves, new - unknown caves and tectonic zones up to 200 m below the surface.

Key words: ground penetrating radar, caves, karst, Divaška Jama, Trhlovca, Slovenia.

Izvleček

Nizkofrekvenčni georadar (GPR), imenovan »Roteg«, smo uporabili pri zaznavi znanih in neznanih rovov Divaške jame in Trhlovce v JZ Sloveniji. »Rotegov« glavne značilnosti so izjemna moč (20 MW) in visoka napetost do 20 kV na antenah, kar omogoča penetracijo, ki je več kot desetkrat globlja, kot jo dosežejo običajni georadarji. Med meritvami smo uporabili 3 m dolgi anteni (50 MHz) s središčno frekvenco 50 MHz. Tako smo po obdelavi podatkov jasno zaznali odboje iz globine 200 m. Med terenskimi meritvami smo izmerili 22 profilov s skupno dolžino 4490 m. Pretnerjeva in Žibernova dvorana v Divaški jami sta bili dobro vidni na georadarskih profilih. Nove velike jame, ki smo jih zaznali pod profil P18, P21 in P22, so skoraj vse na istem nivou, 350–400 m nad morjem. Druga skupina jame na nadmorski višini 420–450 m ustreza Trhlovci. Obe skupini jame sta ločeni z vrzeljo v navpični smeri, ki je verjetno tectonska cona in je dobro vidna na georadarskih profilih. Z uporabo »Rotega« na kraškem površju smo določili znane jame, nove neznane jame in tectonske cone do globine 200 m pod površjem.

Ključne besede: georadar (GPR), jame, kras, Divaška jama, Trhlovca, Slovenija.

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Received/Prejeto: 08.09.2017
INTRODUCTION

The detection of cavities is one of primary goals of GPR method in karst regions (Gosar 2012). Unfortunately, most existing ground penetrating radars (GPR) are unable to detect cavities deeper than 30 m below the ground, even when low frequencies and large antennas are used (Bláha et al. 1999; Hladík & Hruška 1999; Chamberlain et al. 2000; Knez & Slabe 2005; Pavlič & Praznik 2011; Gosar 2012).

In 2014 a new kind of GPR named “Roteg” was developed (RTG-Tengler 2013). Its main characteristic is an extraordinary high power output (20 MW) and high voltage on antennas (up to 20 kV). This is more than two orders larger than in the case of usual GPRs. Such big power allows penetrating more than ten times greater depths than common GPRs.

In 2015 – 2017 we tested “Roteg” GPR at several places (in brackets are positively verified penetrating depths): Pytlíková Cave (20 m) (Kalenda et al. 2016), quarry Malá Dohoda (20 m) (Kalenda et al. 2016), below the quarry Na Bradinách (20 m) (Kalenda et al. 2016), Holštejnská Cave (40 m) (Kalenda & Tengler 2016), Spodní Suchdolská Cave (40 m) (Kalenda et al. 2016), Lopač Cave (20 – 60 m) (Tengler et al. 2016), cave No.561A in the quarry Velká Dohoda (40 m with 1-m antennas - 150 MHz) (Kalenda et al. 2016), cave Amatérská Jeskyně (90 – 110 m) (Tengler et al. 2016), Pekárna Cave (140 m) (Kalenda et al. 2016). After such positive results, we tested the most powerful version in Slovenia above cave system Postojnska – Planinska Jama. We clearly detected caves Jama Na Poti (40 m) (Kalenda et al. 2017b), Črna Jama and Pivka Jama (60 – 70 m) (Kalenda et al. 2018), Postojnska Jama (80 – 150 m) and Planinska Jama (180 m) (Kalenda et al. 2018).

Therefore, the detection of Divaška Jama corridors at depths of 30 – 100 m should not be a problem for “Roteg” GPR. In this study we first repeated part of the measurements performed by Gosar (2012) above Divaška Jama using 50 MHz antenna as a test. Next we prolonged the measurements behind (to the SW) Trhlovca cave to detect undiscovered parts of Divaška Jama and a possible new cave too.

THE GPR METHOD AND LOW-FREQUENCY HIGH-POWER GPR SYSTEM „ROTEG“

GPR produces the short electromagnetic pulses, which are transmitted to the ground by transmitting antenna. The second antenna of the GPR measures the travel time and amplitude of the reflected electromagnetic waves, which are reflected on inhomogeneities (from the viewpoint of electrical conductivity). The delay of the receiving signal depends on the depth of inhomogeneity and velocity of electromagnetic signals in the rock. The velocity of EM signal in rock-mass depends on its permittivity (\(\varepsilon\)) according to the equation (Allred et al. 2008):

\[
v_m = \frac{v_0}{\sqrt{\varepsilon_m \varepsilon_0}}
\]

where:
- \(v_m\) – velocity of the wave propagation through any material
- \(v_0\) – speed of light in air
- \(\varepsilon_m\) – permittivity of the material
- \(\varepsilon_0\) – permittivity of free space or vacuum.

In our case we used the velocity for wet limestone 0.12 m/ns (Cassidy 2009).

The penetration depth is the crucial factor, which limits the applications of GPRs. For high-frequency GPRs, the relatively small penetration depth (only several meters) is due to high attenuation of the high-frequency signal. The penetration depth for low-frequency GPR (below 100 MHz) is limited to dozens of meters mostly by mineralized water, which converts the energy to the heat (Smith & Jol 1995; van der Kruk et al. 1999).

Preliminary test in Moravian Karst (Czech Republic) confirms that in suitable conditions (limestone covered by at least one meter thick soil), the penetration depth is larger than 100 m and in the case of high thickness of wet soil (several meters), the penetration depth decreased to \(\approx 40\) m (Tengler et al. 2016).

The new “Roteg” GPR, compared to the existing GPRs, is characterized by a much higher pulse power (up to 20 MW), higher voltage of antennas (5–20 kV), and in particular by the special design of the pulse generator, which bypasses frequently used semiconductor components MOS and LDMOS, and uses a spark gap instead. This spark gap (discharger) produces Dirac pulses up to 4 ns long by directly discharging capacitors.
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The predominant frequencies are selected from the continuous spectrum by a special antenna, which is tuned to them. The 6-metre long antenna is tuned to the predominant frequency of 25 MHz, the 3-metre antenna is tuned to 50 MHz, and 1-metre antenna is tuned to 150 MHz. Under optimal conditions, when the soil and young sedimentary cover is not thicker than few metres, the reflections of the cave ceiling were clearly detectable using the 6-metre antennas at the depths of around 100 metres under the surface (Tengler et al. 2016).

We used 3-m antennas (50 MHz) and maximal power (20 MW) in the case of measurement above Divaška Jama and behind Trhlovca. We stacked approximately 10 pulses, with the frequency of pulse generation of 120 Hz at a propagation speed of approx. 3 km/h, into one sum with the step of 0.1 m. The accuracy of positioning of the measurement point by on-line GPS was approx. 1 m. The length of records is 2,992 ns obtained with 10.801 samples at 0.277 ns. This corresponds to the converted depth of approx. 360 m at a wave velocity of 12 cm/ns. The sampling frequency was 3.6 GHz. The wave velocity of 12 cm/ns is a table value for typical limestone and it was verified by the curvature of hyperbolas on radarograms.

The REFLEXW program (Sandmeier Software) was used for the data processing. The data was processed using the following sequence:

The signal was amplified with depth, the signal was averaged in x and y axes using 20 samples (elimination of HF noise). Frequencies below 5 MHz and above 40 MHz were filtered to highlight large structures only and remove noise. The used 3-m antennas with 50 MHz central frequency are wide-band antennas with wide frequency band between 5 and 500 MHz. The received signal therefore must be processed in accordance with the purpose of the measurement.

RESULTS

TEST MEASUREMENT ABOVE KNOWN PARTS OF DIVAŠKA JAMA

We started the measurements above known corridors and chambers of Divaška Jama, where common GPR was not successful (Gosar 2012) (Fig. 1).

In Tab. 1 coordinates and lengths of all performed field GPR profiles are presented.

Profile P4_900 started at the main road Divača – Lokev, finished after 300 m at the start of profile P1. The record length was exceptionally set at 15,000 samples (900 m depth). The other profiles (Fig. 1 and 9) were set to the maximum of penetration depth of 360 m, because we were not looking for deeper caves in this area.

Profile P4_900 detected a relatively small cavity at the depth of 30 m at the beginning of the profile (until the position of 40 m) (Fig. 2 – A4). The second important structure is probably a corroded interlayer geological structure (bedding?) with several cavities, which starts at the profile position of 10 m at the depth of 65 m and finishes at the position of 120 m at the depth of 30 m (B4). One small cavity was created on the same structure at the position of 176 m at the depth of 17 m (C4). The third important structure is probably part of Divaška Jama at the position of 190 – 210 m and the depth of 60 m accompanied by another cavity 20 m below it (at the depth of 80 m) at the position 210 – 230 m.

Profile P1 started at the end of profile P4_900 and finished on the forest road. We detected an undiscovered cave at the position between 45 – 65 m at the depth of 50 – 65 m (Fig. 3). It is probably an unknown part of Divaška Jama, which can continue to the north by a deeper corridor below the chamber Pretnerjeva Dvorana.

Profile P2 crossed Divaška Jama and finished at a bush (Fig. 1). The profile of ceiling of the chamber Pretnerjeva Dvorana in Divaška Jama is nicely seen between positions of 33 m and 64 m at the depth of 20 – 25 m (Fig. 4).

Two strong reflections are visible at the beginning of the cave at the position of 8 m and the depth of 45 m and at the end of the profile at the depth of 35 m. Both of them are cavities probably genetically connected with Divaška Jama.

The profile P5, which was planned to be parallel with the Divaška Jama main corridor (Fig. 1), did not show any important cave at the depth between 30 and 70 m (Fig. 5). The most important structure, which is only seen, is probably corroded interlayer geological structure with several cavities, which starts at the beginning of the profile at the depth of 100 m and finishes at the position of 50 m at the depth of 110 m.

Profile P6 started approximately 15 m east of the known end of Divaška Jama and finished behind Trhlovca.

Three important cavities were detected on this profile at the depth of Divaška Jama – at the position of 12 m at the depth of 35 m, at the position of 112 – 120 m at the
Tab. 1: Starts, ends and lengths of profiles according to integrated GPS.

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P4_900</td>
<td>13.948161 45.671864</td>
<td>13.947150 45.674182</td>
</tr>
<tr>
<td>P1</td>
<td>13.947155 45.674222</td>
<td>13.947923 45.674775</td>
</tr>
<tr>
<td>P2</td>
<td>13.947953 45.674795</td>
<td>13.948723 45.674348</td>
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<tr>
<td>(P4)</td>
<td>13.948326 45.674475</td>
<td>13.948342 45.673533</td>
</tr>
<tr>
<td>P5</td>
<td>13.948358 45.673511</td>
<td>13.947561 45.672711</td>
</tr>
<tr>
<td>P6</td>
<td>13.947455 45.672598</td>
<td>13.946964 45.671687</td>
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<tr>
<td>P7</td>
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<tr>
<td>P9</td>
<td>13.948114 45.671853</td>
<td>13.946941 45.672646</td>
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<td>P10</td>
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<td>13.948398 45.672746</td>
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<tr>
<td>P11</td>
<td>13.948408 45.672748</td>
<td>13.947005 45.673838</td>
</tr>
<tr>
<td>P12</td>
<td>13.948038 45.671676</td>
<td>13.947655 45.672574</td>
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<tr>
<td>P13</td>
<td>13.947460 45.672594</td>
<td>13.943733 45.673278</td>
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<tr>
<td>P14</td>
<td>13.943111 45.672982</td>
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<td>13.945195 45.671471</td>
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<td>13.945225 45.671464</td>
<td>13.948046 45.671279</td>
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<tr>
<td>P17</td>
<td>13.948078 45.671320</td>
<td>13.947827 45.671527</td>
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<td>P18</td>
<td>13.946784 45.669352</td>
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<tr>
<td>P19</td>
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<td>13.939089 45.672107</td>
<td>13.935675 45.672882</td>
</tr>
<tr>
<td>P22</td>
<td>13.935571 45.672911</td>
<td>13.931988 45.672145</td>
</tr>
<tr>
<td>P23</td>
<td>13.937355 45.672918</td>
<td>13.937888 45.674506</td>
</tr>
<tr>
<td>P24</td>
<td>13.937879 45.674649</td>
<td>13.941950 45.674406</td>
</tr>
</tbody>
</table>

Fig. 1: GPR profiles measured above known part of the cave Divaška Jama. Blue lines – profiles of Gosar (2012), black curves – profiles of “Roteg” GPR 2017. Red – detected ceiling of the cave (Figs. 4, 7 and 8).
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Fig. 2: GPR profile P4_900.

Fig. 3: GPR profile P1.

Fig. 4: GPR profile P2 and cross-section of Pretnerjeva Dvorana by Gospodarič (1985). The arrow marks the corresponding trigonometric point.
depth of 26 m and at the end of the profile at the depth of 35 m (Fig. 6). Two other important cavities were found at a depth of 115 m and 125 m at positions between 65 and 90 m (Fig. 6). It should be the deeper cave level, which could be connected with Trhllovca, and was detected on profile P11 too.

The most important were two profiles P10 and P11, which were measured above the chamber Žibernova Dvorana (Fig. 1). The big cavity at the depth of 65 m was clearly visible on the radarogram on the profile P10 with the ceiling from the beginning of the profile and end at the position of 50 m (Fig. 7). This is in perfect agreement with the diameter of this chamber and its depth (Fig. 3 in Gosar 2012). Above Žibernova Dvorana there are only two smaller cavities at depths of 35 m and 45 m below the surface at the position of 45 – 50 m.
A similar cavity as on profile P10 can be seen on profile P11 (Fig. 8). The ceiling of chamber Žibernova Dvorana starts at the position of 85 m and its top is at the position of 126 m at the depth of 65 m. This is in good agreement with the cross-section of Žibernova Dvorana on the cave map. The bottom of the Žibernova Dvorana can be at the depth of 85 m, i.e., 355 m above the sea. Another significant reflection can be seen at the position of 80 m and the depth of 110 m. It looks like a corridor of deeper cave level, because almost at the same position it was detected on other profiles, especially south and west of cave Trhlovca.
MEASUREMENTS BEHIND TRHLOVCA CAVE TO THE SW
On the course of two forest roads and one hunting footpath to the south and west of Trhlovca we measured 12 profiles (P12 – P24) of the length between 31 and 408 m (Fig. 9 and Tab. 1).

We found and interpreted cavities, which are marked on Fig. 10 and listed in Tab. 2.

**Fig. 10: Interpreted unknown large cavities detected by GPR. Numbers mark the depth; letters mark the cavities - see text and Tab. 2.**

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Depth</th>
<th>Lon</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45.674613°</td>
<td>13.947492°</td>
<td>45 m</td>
</tr>
<tr>
<td>B</td>
<td>45.673198°</td>
<td>13.946906°</td>
<td>60 m</td>
</tr>
<tr>
<td>C</td>
<td>45.671975°</td>
<td>13.947049°</td>
<td>110 m</td>
</tr>
<tr>
<td>D</td>
<td>45.671108°</td>
<td>13.947064°</td>
<td>65 m</td>
</tr>
<tr>
<td>E</td>
<td>45.669801°</td>
<td>13.945870°</td>
<td>125 m</td>
</tr>
<tr>
<td>F</td>
<td>45.672064°</td>
<td>13.945886°</td>
<td>35 m</td>
</tr>
<tr>
<td>G</td>
<td>45.672121°</td>
<td>13.944032°</td>
<td>65 m</td>
</tr>
<tr>
<td>H</td>
<td>45.671800°</td>
<td>13.939920°</td>
<td>60 m</td>
</tr>
<tr>
<td>I</td>
<td>45.672735°</td>
<td>13.937636°</td>
<td>125 m</td>
</tr>
<tr>
<td>J</td>
<td>45.674315°</td>
<td>13.937689°</td>
<td>60 m</td>
</tr>
<tr>
<td>K</td>
<td>45.672760°</td>
<td>13.936240°</td>
<td>35 m</td>
</tr>
<tr>
<td>L</td>
<td>45.672274°</td>
<td>13.932838°</td>
<td>135 m</td>
</tr>
</tbody>
</table>

Tab. 2: The interpreted positions of centres of found cavities on GPR profiles measured behind cave Trhlovca. The depth was evaluated for the velocity \( v = 12 \text{ cm/ns} \) and the position is the nearest point of the cavity to the profile (without migration).

The cavity A – NW from Pretnjerjeva Dvorana.
The cavity A was found on the profile P1 (Fig. 3). A relatively large cavity (20 m wide) was found at several levels between 40 m and 60 m below the surface at the position of 45 – 70 m. This depth corresponds to the bottom of Pretnjerjeva Dvorana, which means that there should be inflow or outflow corridor to/from old active Divaška Jama.
The cavity B – NW from Žibernova Dvorana
The similar large cavity was found on the profile P4_900 at the depth between 60 and 90 m below the surface at the position of 190 – 220 m (Fig. 2). Some relatively small parts of this cavity are free of sediments, indicated by strong reflections, but the total height of the cavity should be at least 20 m (the difference between reflection depths from the ceiling and the bottom). It should be part of Divaška Jama.

The cavity C – S of the known end of Divaška Jama
Profile P6 crossed the large cavities at the depth of 110 – 130 m below the surface at the positions of 70 – 90 m (Fig. 6 – D6). Below the same profile P6 there are several cavities at the depth of the end of Divaška Jama or cave Trhlovca, i.e., 25 – 35 m (Fig. 6 – A6, B6 and C6). The same was found at the beginning of profile P4_900. It means that there are two cave levels and it is not clear, which of them was the main outflow from Divaška Jama at the time of active flow through it.

The cavities D - S of the known end of Divaška Jama
Large cavities (D) were found at the depths of 40 – 80 m on profile P16 at position of 90 – 200 m (Fig. 11). The width of these cavities is between 20 and 40 m, which correspond to the diameters and position of Divaška Jama. We suppose that these cavities represent an unknown extension of Divaška Jama and the main corridors went through the cavity F, which is near Trhlovca (see next paragraph).

The cavities E - S of the known end of Divaška Jama
The most southern profile P18 detected between positions of 30 and 150 several cavities (most of them with air, which is detectable by the sequence blue-red-blue on radarograms as the wave is travelling from limestone to air, than to sediments and back to limestone) at the depths of 60 – 110 m. All of them are tied to the presumed fault zone (see Fig. 23), which divides the massif into two different parts. The eastern part (left on Fig. 12) is full of caves and cavities and the western part (right on Fig. 12) is practically without karst phenomena. We think that these cavities are part of Divaška Jama because of the same depth and diameters.

The cavities F – above the Trhlovca cave
Several cavities F were found at the profile P12 at depths from 15 m to 60 m. The profile P12 passed above Trhlovca at the position of 160 – 210 m (Fig. 13). Many of detected cavities are known at the depth of 40 m, but the caves deeper than 60 m below the surface are not known yet. The cavity at the depth of 40 – 50 m at the position of 70 – 105 m belongs to group D. It should be a part of Divaška Jama.
The cavities G – W of the Trhlovca cave

Both profiles P13 and P15 (Figs. 14 and 15) show an important cavity of large length. It looks like corroded interlayer surface or an overthrust. The slope of this surface is to the south parallel to the layers in the surroundings. This surface continues to the profile P12, where is at the depth of 15 m and is clearly visible in the entrance of Trhlovca (the whole upper cave is based on this structural geological layer or thrust fault).

The cavities H

On the profile P19 there are several important cavities only around the position of 340 m at the depths of 15 m, 50 m and 60 m (Fig. 16). They are at the depth of 55 – 60 m (445...
– 450 m a.s.l.), which is at the same position as the upper
cave level in Trhlovca and the surface above Divaška Jama.
These caves should not be connected to Divaška Jama.

The cavity I
The largest cavity I at the position of Divaška Jama (370 –
420 m a.s.l.) was found at the depth of 140 m (360 – 375
m a.s.l.) on profile P21 (Fig. 17). The length of the ceil-
ing is approximately 90 m (between positions 60 m and
150 m). Both ends of the cavity I are marked by strong
hyperbolas in the same way as on the profiles P2 or P10
for example. There are many other cavities or caves at the
positions between 160 – 270 m at the depth of 20 – 55 m.
They are connected with the fault zone, which is visible
on the surface at the position of 215 m.

The other large karst object at the level of Divaška
Jama was found on the profile P23 at the depth of 95 –
120 m below the surface (Fig. 18). It confirms that there is
another large corridor besides Divaška Jama at the same
level. This corridor was crossed by profiles P21 and P23.

The cavity J
The cavity J was developed on the interlayer geological
structure or thrust fault at the end of profile P23 at the
depth of 60 m (Fig. 18) and is visible on the profile P24
too (Fig. 19). Probably it is the same structural geological
element, which was detected on profiles P12, P13 and
P15 (Figs. 13, 14 and 15). This structural geological ele-
ment must be extraordinarily susceptible to corrosion.

The cavity K
Many other cavities were detected at the end of the profile
P21 (between positions 200 m and 260 m) at the depth
of 15 – 40 m around the large tectonic zone of the 10 m
width, which was found at the position of 210 – 220 m
(Fig. 17). This zone is filled with sediments, especially
to the depth of 10 m, which does not allow the radar
signal to penetrate large depths (more than 60 m).

The cavity L
The last big karst object – cavity L – was found at the
end of profile P22 (position 230 – 280 m) at the depth
of 130 – 150 m (Fig. 20 – cavity L). Because located at
the end of the surveyed area, the orientation of this
huge corridor is not known. The level is the same as
for Divaška Jama, i.e., 365 – 390 m a.s.l. and the width
of cavity (and reflection amplitude) is similar (several
dozen of meters).

DISCUSSIONS

PENETRATION DEPTH
The penetration depth depends mostly on the properties
of the rocks and, especially, the sedimentary cover, which
consists mainly of clay minerals with water, which has
high permittivity and high conductivity. In the karst ar-
eas, the sedimentary cover is usually very thin and lime-
stone has low conductivity and permittivity, which is advan-
tageous for radar measurements. However, the com-
mon GPRs have the penetration depth less than 30 m,
even when low frequencies and large antennas are used.
Smith & Jol (1995) experimentally estimated that the
penetration depth for 25 MHz antenna and Quaternary
sedimentary environment (above the level of mineral-
ized water) is between 52 and 57 meters. For 100 MHz
antenna the penetration depth was reduced to 37 m. The
results of experimental measurements above Divaška
Jama (Gosar 2012) confirmed previous estimations. The
problem is in the maximum power output at common
GPRs, which does not reach 1MW because semiconduc-
tors do not allow switching big currents and short pulses.
The “Roteg” GPR uses spark gaps instead of semiconduc-
tors, which allow producing pulses of the length of 3–4 ns
with the maximal voltage on antenna 20 kV. The power
output reaches up to 20 MW in the pulse regime.

During the measurement in the Divaška Jama area
we used 3-m antennas with central frequency of 50 MHz
and we clearly detected the reflections from the depth of
200 m after data processing (filtering, stacking and aver-
aging in both x and y axes) (see for example Figs. 20 and 11). The ceiling of Divaška Jama at the depths of 40 – 60 m was detectable right in the field after stacking several samples only (Figs. 4, 7 and 8).

HORIZONTAL AND VERTICAL RESOLUTIONS
The theoretical vertical and horizontal resolutions depend mainly on the length (width) of the pulse and the velocity of EM waves in the rocks. The vertical (range) resolution is not a problem, because, according to Annan (2009), the range resolution \( r \) is

\[
 r = v_m \times \frac{W}{4} ,
\]

where \( v_m \) – velocity of the wave propagation through the material and \( W \) is pulse width. The velocity depends only on the permittivity of the material. In our case we used the velocity \( v_m \) for wet limestone 12 cm/ns (Cas-sidy 2009). For 50 MHz antenna and limestone \( r \) should be less than 1 m, which allows detecting the typical caves in the area.

The theoretical horizontal (lateral) resolution \( L \) between two in-homogeneities depends on the length of the pulse and the velocity of EM waves in rocks according to the equation (Annan 2009)

\[
 L = \sqrt{v_m \times W \times \frac{d}{2} ,}
\]

where \( d \) is the depth (distance from the GPR). For 50 MHz antenna, limestone and the depth of 100 m, \( L \) should be less than 11 m. For the depth of 50 m, \( L \) should be less than 8 m. If we use instead of the wavelength the width of pulse, which is for “Roteg” GPR 3 - 4 ns, the lateral resolution will be 4.25 m only at the depth of 100 m. We can compare the theoretical lateral resolution with the observations of the diameter of the chamber ceilings of Divaška Jama. We measured three profiles above Pret-nerjeva Dvorana and Žibernova Dvorana. The first and last deviations of the hyperbola course at the ends of the “flat” part of the reflection mark the beginning and end of the ceiling.

The “beginning” of the cave on the profile P2 is at the position of 33 m at the depth of 22 m (Fig. 4). The “end” of cave can be assumed at the position of 84 m at the depth of 25 m. When we compare these points with
the contours of Divaška Jama (Figs. 1, 10 or 21), we can see that lateral error is less than 5 m.

The “beginning” of the cave on the profile P10 is outside the radarogram at the depth of (approximately) 67 m (Fig. 7). The “end” of cave can be assumed at the position of 54 m at the depth of 65 m. When we compare this point with the contours of the Divaška Jama (Figs. 1, 10 or 21), we can see that lateral error is less than 5 m.

The “beginning” of the cave on the profile P11 is at the position of 85 m at the depth of (approximately) 57 m (Fig. 8). The “end” of cave can be assumed at the position of 124 m at the depth of 55 m. When we compare this point with the contours of the Divaška Jama (Figs. 1, 10 or 21), we can see that lateral error is again less than 5 m.

We can compare the GPR method with other geophysical or geological methods:

a) integral methods like Very low frequency method (VLF), Resistivity method (RM), Vertical electrical sounding (VES) or Electrical profiling (EP) are relatively easy, but their penetration depth is less than one half of the electrode separation and the vertical and lateral resolutions are relatively low as we suppose the really square errors E~15% depending on the electrode separation and resistivity contrast (Mariita 1986).

b) differential or point methods like Seismic reflection (SR) or drilling are very precise to the depths of several hundred metres, but they are very expensive (more than several thousand times) in comparison with GPR method.

![Image](https://via.placeholder.com/150)

**Fig. 23:** Lidar map (source ARSO 2017) with GPR “Roteg” profiles (black), tectonics (violet), layers (green and grey) and detected large cavities (orange). Geology after Jurkovšek et al. 1996.
The main limitation factor of using GPR is the penetration depth, which for common kinds of GPRs in common conditions (crystalline rocks and soil cover) reaches only several metres (Bláha et al. 1999). Because the new kind of GPR – GPR “Roteg” – has more than 100 times bigger power output and the high sensitivity for low frequencies, especially using 6-m long antennas, the penetration depth is much bigger than for common kinds of GPRs. The positive tested penetration depth of Roteg GPR in the suitable conditions like limestone with small or no cover is much bigger than several hundred metres.

CAVE LEVEL(S)
When we compare the elevations of all recognised caves on the long profile, composed of several radarograms, measured from the road Divača – Lokev to the end of profile P22 W of the Klemenka hill (Fig. 22 or 23) with the vertical cross-section of Divaška Jama, we can see that all big cavities, which were detected below profiles P18, P21 and P22 are almost at the same level of 350 – 400 m a.s.l. (Fig. 22). There is also another group of cavities at the level of 420 – 450 m a.s.l., which corresponds to Trhllovca. Both groups are separated by the gap which extends in the vertical direction, and is visible almost everywhere and probably presents tectonic zone (Fig. 22).

TECTONICS
The main fault and fault zones were recognisable not only on the Lidar map by the surface morphology and structural discontinuities, but many of them were clearly visible on radarograms. The good example of the fault zone is on profile P1 at the position of 77 m (Fig. 3). One of the best expressed faults was detected by three profiles – P18 at the position of 0 m, on profile P15 at the position of 280 m (Fig. 15) and on profile P12 at the position of 300 m. The other important fault zone is clearly visible on the profile P12 at the position of the cave Trhllovca (Fig. 13). Two big faults are visible on profile P21 at the positions 110 m and 212 m (Fig. 17).

Evaluation of the tectonic pattern of the measured area (Fig. 23) showed that courses of the caves follow the prevailing tectonics and fault system pattern not only in Divaška Jama, but everywhere in the study area.

CONCLUSION
At first we tested the penetration depth of novel GPR system above known parts of Divaška Jama and found that ceilings of big chambers are clearly detectable at depths of more than 60 m below the surface.

During the next measurements south and west from Trhllovca cave on an area approximately 1000 x 300 m we found the possible continuation of the Divaška Jama and other large caves at the same level (approximately 360 – 410 m a.s.l.).

The penetration depth of the GPR “Roteg” was surely more than 200 m using 3-m antennas, 50 MHz frequency and maximal voltage output of 20 kV on transmitting antenna.

We prepared a geological sketch based on Lidar map (ARSO 2017) and we estimated possible tectonic zones, which are close to recognised large cavities and caves at the Divaška Jama level (Fig. 23).

By the use of GPR “Roteg” on karst surface we were able to detect known caves, new unknown caves and tectonic zones up to 200 m under surface.

ACKNOWLEDGEMENTS

Study was financially supported by „Karst Research Programme“ (P6-0119), EPOS IP project (ZRC SAZU), Ing. Rudolf Tengler – RTG and CoalExp Pražmo. We are greatful to Dr. Trevor Shaw for English text improvement.
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