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Technical note

Acoustic analysis of the glacier caves in Svalbard

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ABSTRACT

Glacier caves are unique and spectacular wonders of nature that can be found in very few places in the world. They have different shapes, capacity or wall structures that most often form anew every winter season. The article explores an interesting aspect of glacier cave acoustics as these spaces have never been investigated in that respect. The paper shows the methods and results of spatial impulse measurements in four different glacier caves of the Svalbard archipelago located near the city of Longyearbyen. The basic room acoustic parameters together with Sound Pressure Levels have been measured or calculated together with parametric statistical analysis. The results show the diversity of acoustical climates inside the glacier caves that strongly depends on the morphology and dimensions of the caves. The analysis of measurement locations (within particular caves) shows the strong influence on sound absorption by the snow located at the entrance of the caves. The conducted research shows the potential of acoustical measurements in the process of monitoring the cave morphology and therefore climate changes as well.

1. Introduction

Caves were probably the first symbolic shelter of our ancestors. To this day, they are a fascinating goal of research, exploration and legends. According to a dictionary with terminology related to caves and selected concepts from geology [1]: “a cave is a natural space (emptiness) in the ground or rock of the size that enables exploration by a human being”. The main subject of this work is glacier caves which, due to their availability, variability and difficult weather conditions, have not been subjected to acoustic analysis before. In particular, this applies to the glacier caves in Svalbard. However, a number of hydrological analyses [2,3] are available, in which the acoustics factor could certainly be an added value, in particular due to climate changes.

A related, but often over-interpreted, notion is an ice cave, that is, a rock formation in which there is all-year glaciation, snow or ice in different forms. This name is often used in relation to caves located in glaciers, whose correct name is glacier caves [1]. The mechanism of glacier cave formation is quite simple. Most often, water that comes from the surface layer of the glacier melts and flows down into the ice and out of the glacier at the base level. The exchange of heat from the water can result in a temperature sufficient to melt the ice and form an air-filled cavity. Then, the air movement can help the recess to expand by melting in the summer and sublimation in the winter. Such ice caves usually have translucent walls that let in blue light. A second type of glacier cave is formed when icy winter air settles on the floor of glacier, from where it cannot be supplanted or when moisture (water vapor) freezes under the influence of cold air currents. Formations of frozen lakes, icicles and of icing are very common. Icicles similar to helictites are also created where the air currents reflect off the freezing water. Some glacier caves are relatively unstable due to melting and glacier movements, undergoing local or complete breakdowns, as well as destruction by collapse. There are also caves (e.g. in Iceland) that are formed as a result of the geothermal and volcanic activity of hot springs located under snowfields or glaciers.

The world’s largest caves include the Hang Son Doong cave located in the Phong Nha-Kẻ Bàng National Park in Vietnam and the Mammoth Cave National Park – the world’s longest cave system (652 km). Škocjan Caves was entered onto the UNESCO World Heritage List in 1986. One of the larger glacier caves is a cave in the Erebus Ice Tongue glacier in Antarctica (about 12 km). Caves create a specific acoustic system. It is a closed or semi-open area bounded by walls of very diverse geometry and structure. Characteristic features of sound propagation in caves are its multiple reflections from the walls and insulation from the external environment, so usually there is a very low level of acoustic background. Caves have very diverse resonance frequencies and, in addition, through naturally formed regular, round shapes, the sound in some parts of caves is strengthened. For example, Reznikoff [4] compared the

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relationships of the most resonant places with the map of the location of rock paintings in palaeolithic caves, among others in France, which indicates the importance of the acoustic factor in the morphology and history of caves. There are many caves in the world where interesting acoustic phenomena can be found. Many of these phenomena are associated with air flows in caves, e.g. the Vjeternica cave in Bosnia and Herzegovina, from which various sounds are formed by the air flow at the speed of about 3 m/s. Rikavica Cave is named after the sounds generated by the air compressed by sea waves in the crevices of the cave.

Generally, there are not many works concerning the acoustics of caves and there are hardly any about glacier cave acoustics. However, there is an interesting reference [5] about the acoustics of several stone caves in Italy. The current study shows the differences and similarities between stone and glacier cave formations.

The second paragraph describes the morphology and locations of the measured glacier caves. The third section explains the simplified measurement methods due to the difficult logistics of the polar environment. The next paragraph shows the obtained results together with the basic parametric statistical analysis. The fifth section provides an additional analysis of the relation between the reverberation time and the measurement point location. The article is summarized in the last paragraph together with some insights and future work.

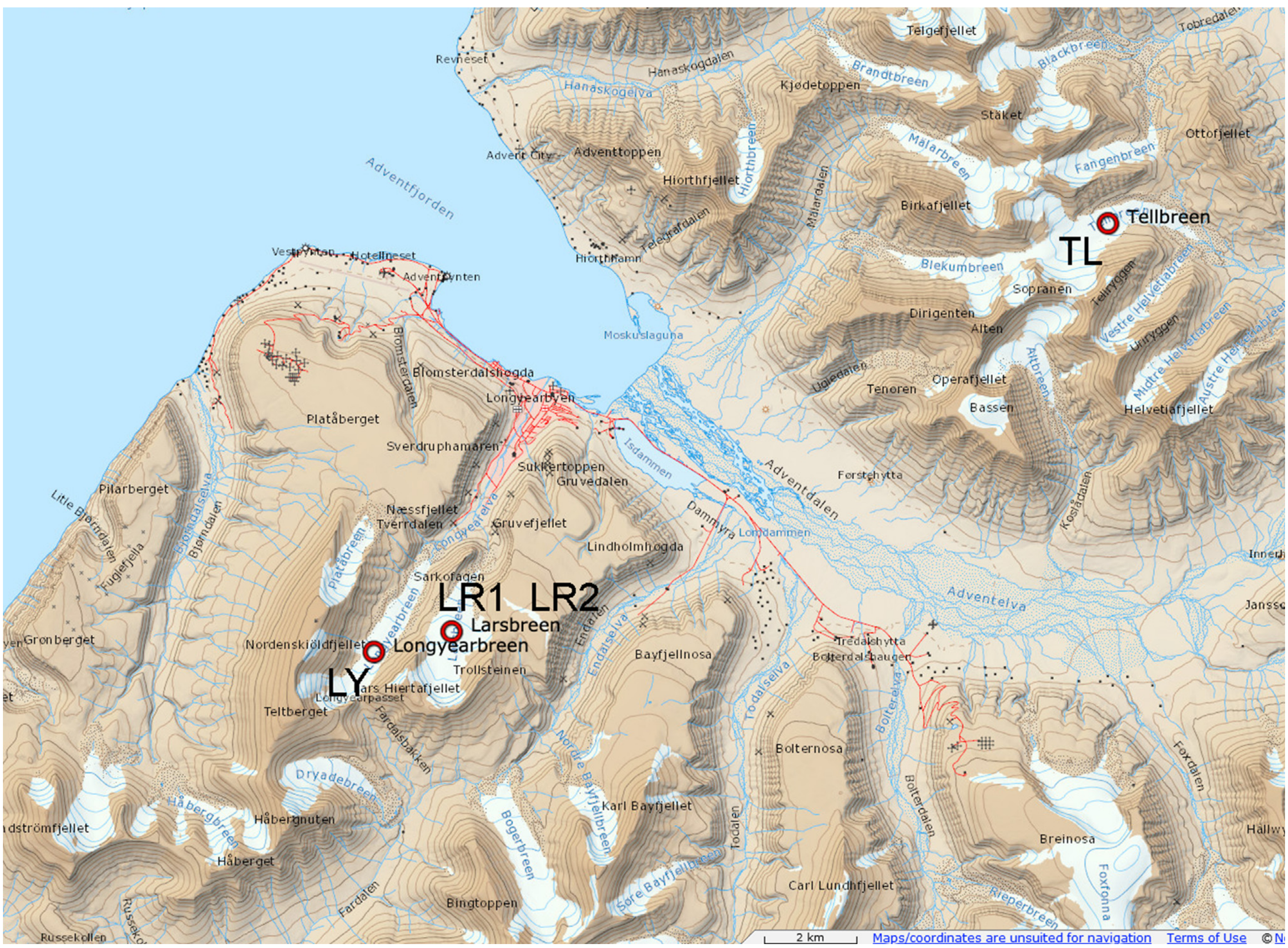

Fig. 1. Location of glacier caves where the acoustical measurements were made.

a) b)

Fig. 2. Entrance to glacial caves: a) exposed hatch, b) snow tunnel leading to the cave.

2. Time and place of research

The research was carried out during two research expeditions, at the turn of February and March 2017 and in March 2018. During the first winter visit to the Svalbard archipelago, a reconnaissance and initial exploration of three caves located in Larsbreen (LR) and Longyearbreen (LY) were carried out. These glaciers are separated by the Sarcophagen peak and descend into the Longyeardalen Valley (Fig. 1). Acoustic background and geometry measurements were made and several impulse responses were recorded using the balloon impulse method.

During the next trip in 2018, appropriate equipment was prepared for deeper exploration of the caves and devices enabling much more accurate measurements of the spatial impulse responses. Measurements were made in the same caves as in the previous year, and additional measurements were made in a cave on the Tellbreen Glacier (TL), located about 20 km from Longyearbyen. The location of the examined ice caves is shown in Fig. 1. The

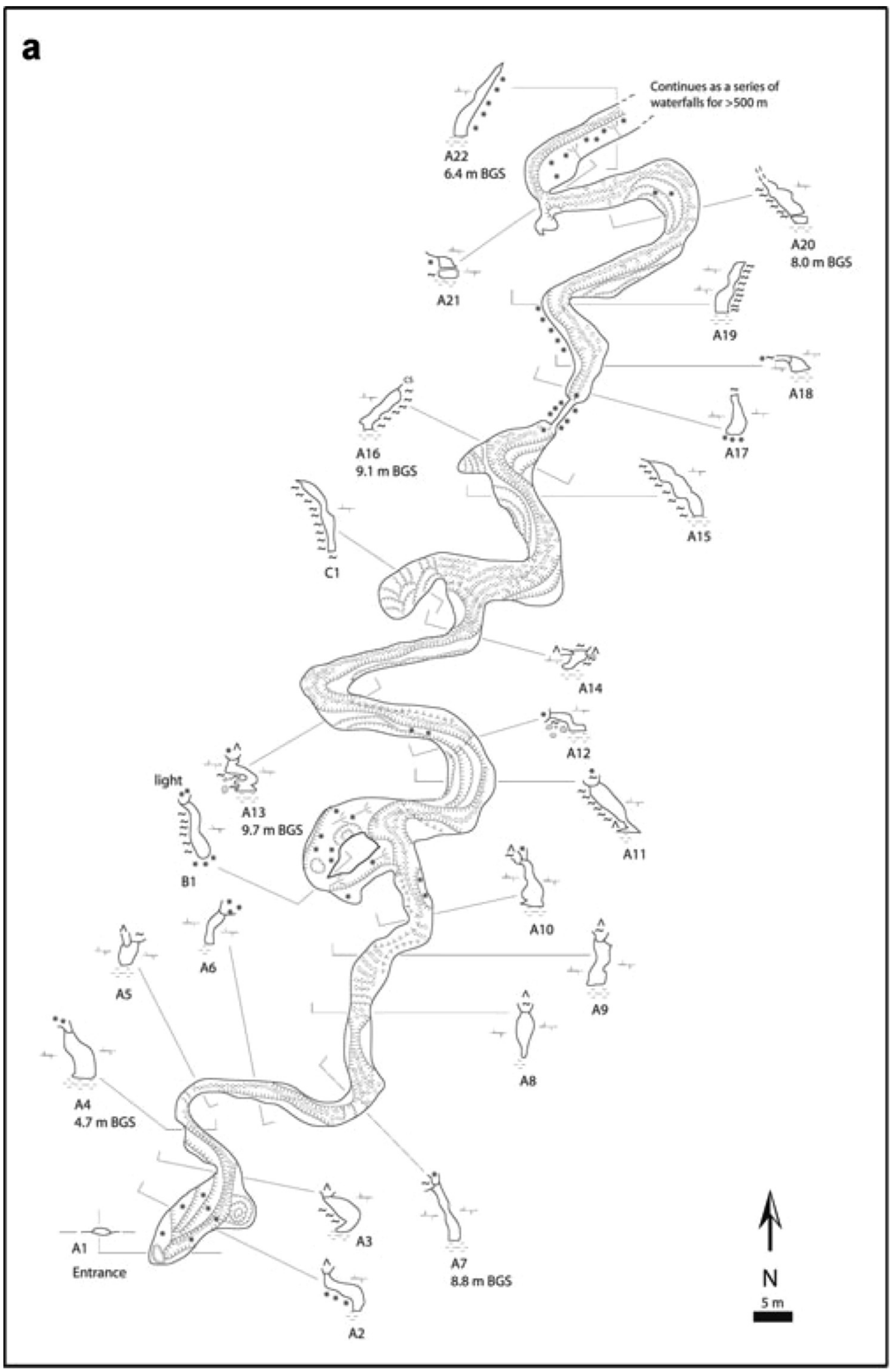

Fig. 3. Plan view of conduits surveyed on Longyearbreen (October 2006) by [6].

LR1, LR2 and LY caves were accessible on foot from Longyearbyen, and the TL cave by snowmobiles.

The studied caves were characterized by large geometrical diversity, both among themselves and in time, i.e. shape, glaciation and others were completely different in 2017 and 2018. The well-protected, marked and prepared entrances to the caves (Fig. 2) were in the same location.

The exact morphology of the studied caves (LY and TL) and the characteristics of the glaciers in which these caves are located are described in [6] and [7]. The description and analysis of the LY cave in the reference [6] refer to the state at the turn of 2006 and 2007, and TL: 2011–2013. Fig. 3 shows the map of the Longyearbreen cave by the authors of reference [6].

In 2018, inside the cave were all the typical internal formations for this type of cave. Due to the lack of adequate knowledge and experience of the team performing acoustic measurements, no such detailed analysis was performed as in [6,7], but photographic documentation was made (Fig. 4) as well as sketches of cave geometry. Inside the studied caves, ice corridors dominated (Fig. 4a), evenly or partially icy (e.g. one wall with ice and one snow wall – Fig. 4b).

In many places, multi-layered internal formations, frozen moraines in the form of small gravel and boulders, the diversity of which is illustrated in Fig. 4c-e, have been noticed. Some of the walls were heavily or partially frosted (Fig. 4f). It was very interesting to descend to the head of the glacier at the bottom of the LR2 cave, where the frozen moraine in the form of medium-sized stones dominated (Fig. 4g). At the very end of the cave, there was a high chimney leading almost to the surface of the glacier (Fig. 4h).

3. Measuring methods

Measurements of classic acoustic parameters of selected glacial caves were made in 2018. EASERA [8] software and scripts in MATLAB were used to determine the spatial impulse responses in

Fig. 4. Morphology and diversity of the caves studied: a) ice corridor, b) corridor with one ice wall and one snow wall, c) multilayer internal formations, d) frozen moraine, e) heavily frosted walls, f) frozen boulders, g) forehead of the glacier - bottom of the cave, h) chimney at the bottom of the cave.

the caves under study. Measurements were made following the ISO 3382-1 standard [9], but due to the specificity of space and logistic constraints, instead of an omnidirectional sound source, an Ultimate Ears BOOM 2 [10] (portable, commercial sound source) was used. The parameters of this device have been previously tested [11]. Fig. 6 shows the amplitude-frequency characteristics based on the measurements in the UST-AGH anechoic chamber [12]. As a measuring microphone, a first-order Soundfield SPS 200 [13] ambisonics microphone was used to determine the spatial features of the sound field and to later use the recorded impulse responses for multi-channel auralization (Fig. 5).

Such an amount of equipment caused a logistical problem because the caves can only be reached by snow mobiles in some areas and on foot in the protected zones. All the devices were packed in reduced soft cases, together with spare clothes, food and snow-ice tracking equipment, such as ropes and crampons etc. In the LY cave there was about 10 m of ice shelf on the way to proceed, so basic climbing skills and equipment were also necessary.

Basic acoustic parameters were calculated on the basis of a pressure signal from an ambisonic microphone (component W of B-format), whose frequency response was previously measured. In the acoustic range, its characteristic is linear with a deviation of not more than ±3 dB. Test signals (10-second logarithm sine sweep) were recorded using a ZOOM H4n portable sound recorder [14]. The signals were recorded with 24-bit resolution and a sampling frequency of 44.1 kHz.

In addition, the background sounds and sound pressure level generated during the determination of the impulse response were recorded during the measurements. A SVAN 959 sound analyser

Fig. 5. a, b) Ambisonic microphone and sound pressure level meter in the studied cave corridors.

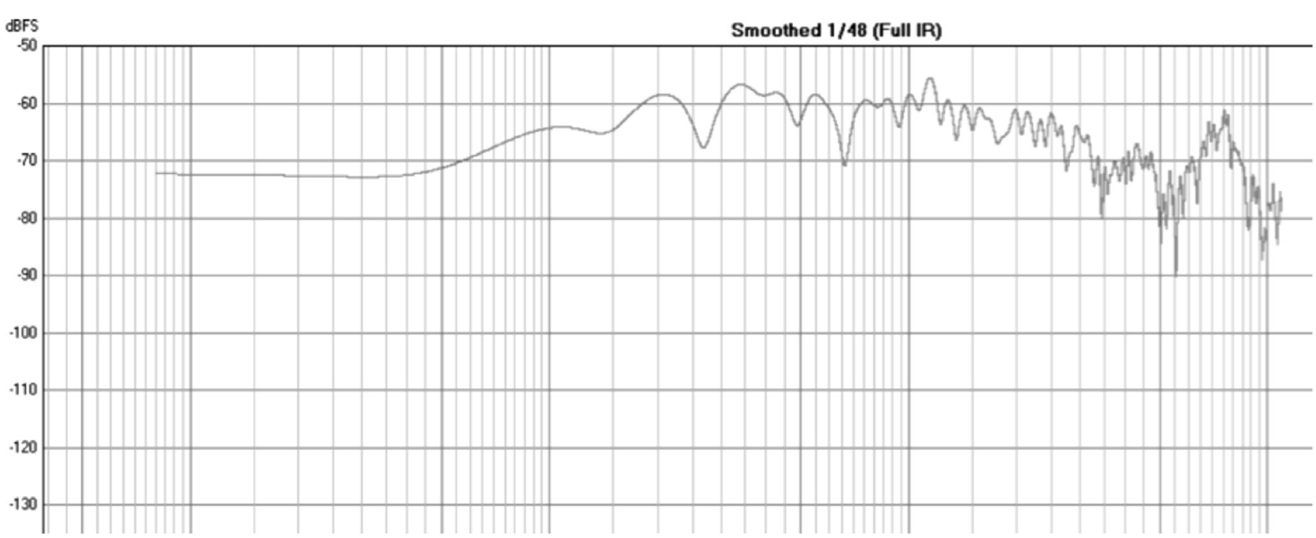

Fig. 6. Frequency characteristics of the Ultimate Ears BOOM 2 loudspeaker.

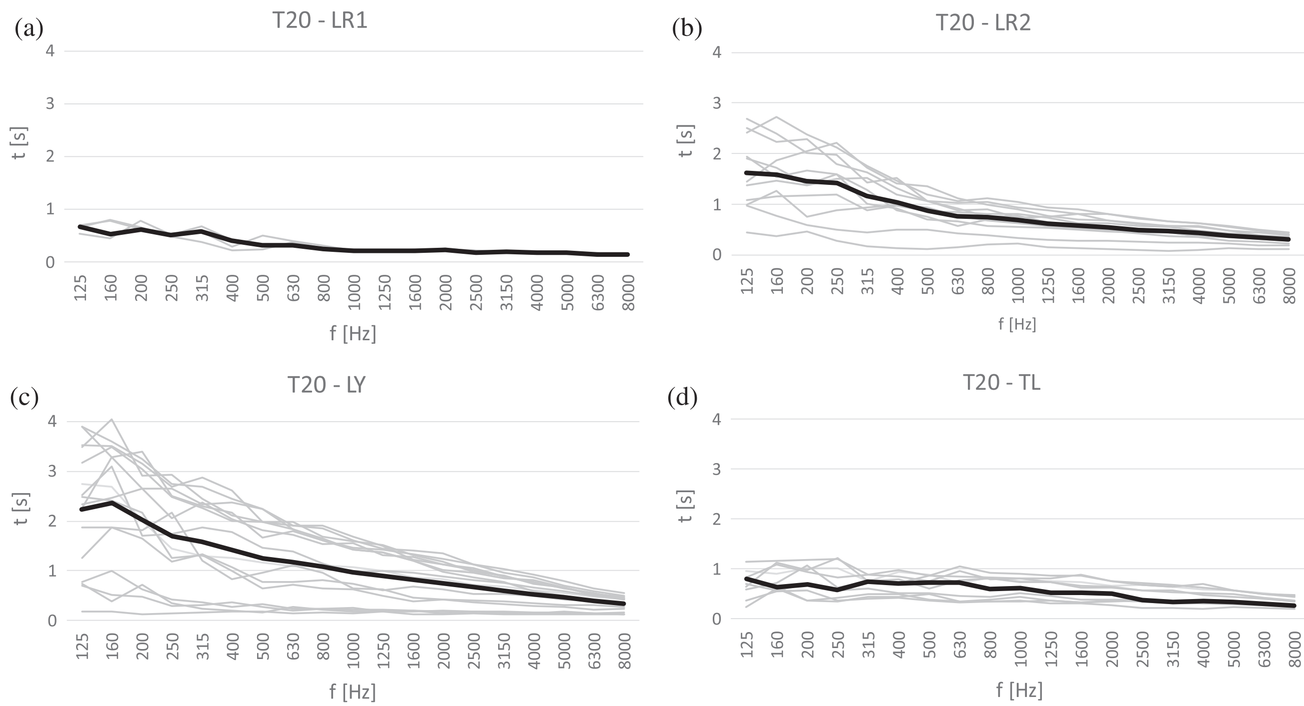

Fig. 7. T20 reverberation time in the: a) LR1, b) LR2, c) LY and) TL caves; thin, gray lines show results from individual measurement points, and the bold black line shows the median value.

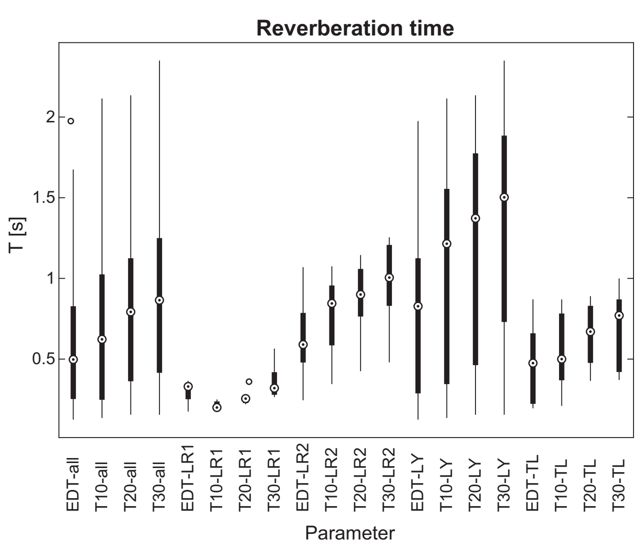

Fig. 8. Box chart of reverberation time distribution of T10, T20, T30 and early EDT decay time of the studied caves.

equipped with a ½″ 40AE free field microphone by G.R.A.S. and an SV12L microphone preamplifier was used in order to measure noise levels.

Due to the minimization and limitations of the measuring apparatus, the output test signal was recorded without synchronization with an input test signal (separate playback and record devices were used). In order to calculate acoustic estimators, the impulse response h was calculated by deconvolution of the test signal s, which was a 10 s logarithmic sine sweep (1) where s_T is the test signal recorded in ice caves.

$$h(n) = F^{-1}\left[\frac{s_T(f)}{s(f)}\right], \tag{1}$$

4. Results

There were around 50 impulse responses measured in all 4 glacier caves. The number of measurement points in each cave depended on its length and morphology complexity, so the distance between subsequent points varied from about 5 to 20 m. Basic room acoustic estimators were calculated, such as: Reverberation time (RT), Early Decay Time (EDT), Bass Ratio (BR), Treble Ratio (TR), Clarity for Speech and Music (C7, C50 and C80), Sound definition (D) and Speech Transmission Index (STI). All the parameters were calculated according to the ISO 3382 standard [9] using Easera software [10].

4.1. Reverberation time

Fig. 7 a)-d) shows the T20 reverberation time as a function of frequency at all points of the caves under study. The medians of individual values are marked in bold. Fig. 8 shows the parametric statistical distribution of early decay time (average of 500 and 1000 Hz octave bands) and reverberation time calculated using various methods (T10, T20 and T30: average of 500 and 1000 Hz). The reverberation time of the studied caves is characterized by a large dispersion of values. This is due to the very variable geometry of individual caves, but primarily with the degree of glaciation, frost or snow, as well as the type of ground. The lowest values of reverberation time and early decay time, as well as their smallest variability, are observed for the LR1 cave. The median EDT is about 0.25 s, and for T20 about 0.2 s. On the other hand, the LY cave has the greatest variability. The median EDT is about 0.8 s and the T20 is about 1.4. Maximum values oscillate within 2-second limits.

The frequency characteristics of the reverberation time of all the investigated caves in the low frequency range (up to about 600 Hz) is very diverse and has different local extremes for each measurement point. Above the frequency of about 1 kHz, the curve is flat and falls monotonically, almost for every measurement. It

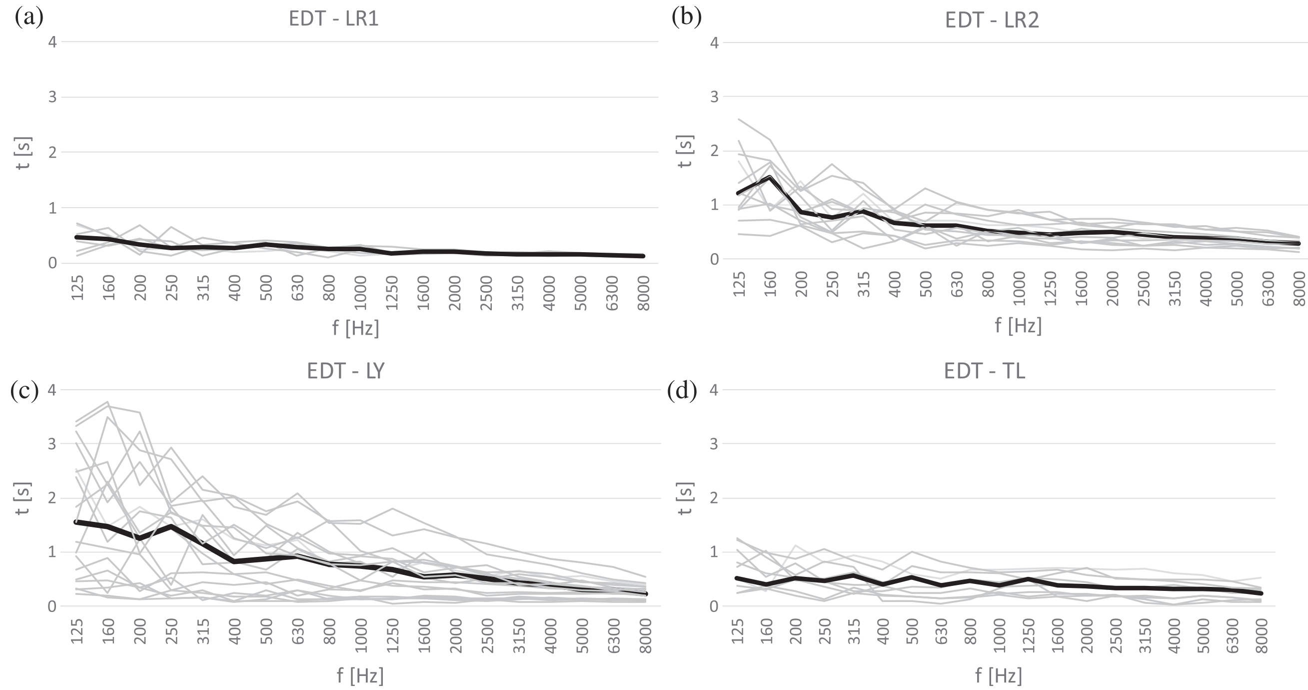

Fig. 9. Early Decay Time in the a) LR1, b) LR2, c) LY and) TL caves; thin, gray lines show results from individual measurement points, and the bold black line shows the median value at individual frequencies.

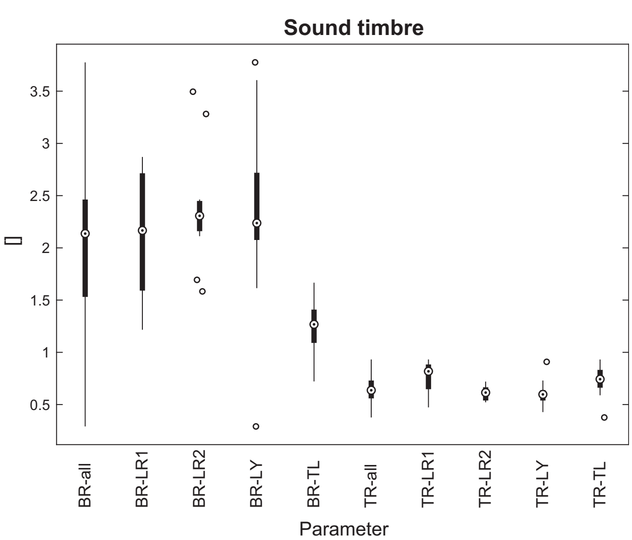

Fig. 10. Box chart of the distribution of the BR bass factor and high tones TR of the examined caves.

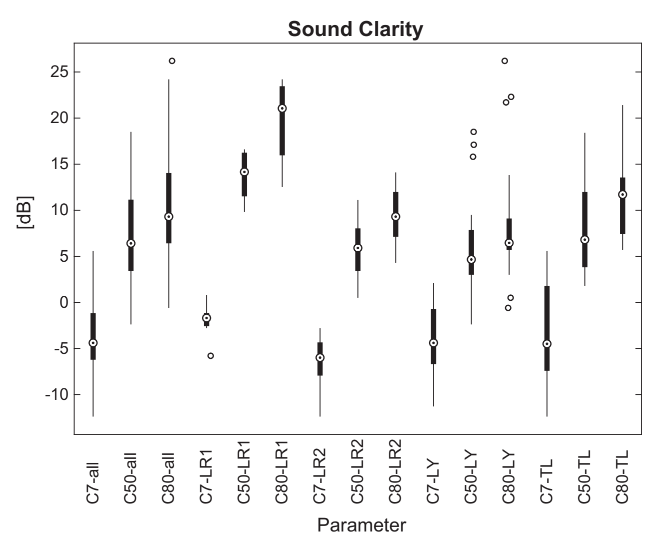

Fig. 11. Box chart of the distribution of C7 sound clarity, sound clarity for C50 speech and C80 music of the studied caves.

can be concluded that there is a dominance of wave phenomena at resonance frequencies and a stochastic nature of the sound field at medium and high frequencies. The local accumulation of curves in the LY cave are also of interest. Three clusters with short (0.25 s), medium (1 s) and long (over 2 s) reverberation time can be observed. In the remaining caves, the distribution of curves is relatively even.

Fig. 9 a)-d) shows the EDT early decay time as a function of frequency at all points of the caves under study. Curve shapes are definitely more irregular than for T20 reverberation times, and the values are generally lower (except for extremes, which are similar).

4.2. Timbre parameters, clarity and intelligibility of speech

In terms of timbre, all the examined ice caves are relatively homogeneous (Fig. 10). The median of the BR bass indicator is in the range of 2.1–2.3 for the LR1, LR2 and LY caves, and is about 1.3 for the TL cave. The median of the TR parameter varies from 0.5 for LY to 0.7 for LR1, and the TR variation distribution is much smaller than BR. The timbre of glacier caves can therefore be described as dark or bass.

The sound clarity of the glacier caves is relatively high (Fig. 11). Besides the LR1 cave, the median clarity for speech is between 4 and 8 dB, and for music about 2 dB more. The LR1 cave is characterized by much higher clarity (almost 10 dB).

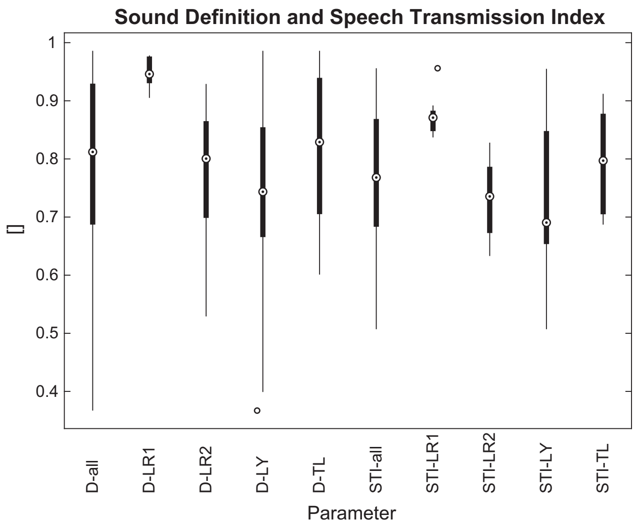

Fig. 12. Box chart of the sound definition distribution D and the STI speech intelligibility index of the studied caves.

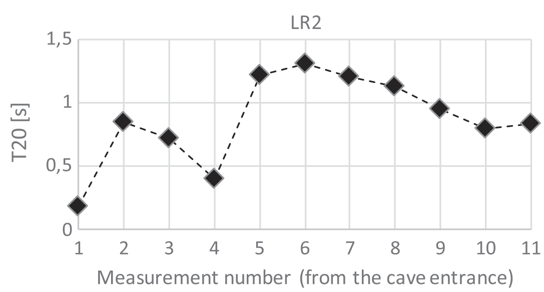

Fig. 13. T20 reverberation time (average for 500 and 1000 Hz) in the LR2 cave with measurement order.

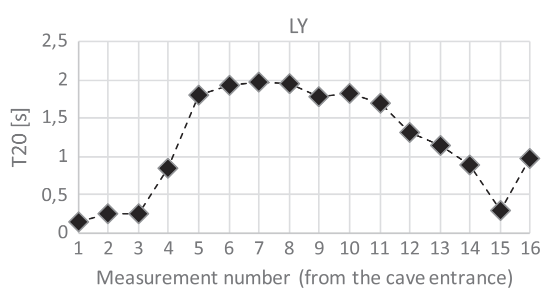

Fig. 14. T20 reverberation time (average for 500 and 1000 Hz) in the LY cave with measurement order.

Fig. 12 shows the selectivity of D and the intelligibility of STI sound. By definition, the parameter D is strongly correlated with C50, so the distribution of results is also similar. Speech intelligibility can be described as very good or excellent. Only the extreme values for the LY cave have values defined as good or sufficient. The calculations of sound clarity C and sound definition D in Figs. 11 and 12 are calculated for broadband impulse response without filtering.

4.3. Sound pressure level

The noises produced by the measuring system working as a sound level meter is around 15 dB (A) (measured at the AGH University of Science and Technology and declared by the manufacturer) [15]. All the measurements taken in the absence of people result in levels below the device range. It can be stated that, due to the very specific conditions, barely no life and thick, hard ice walls, the glacier caves could be the among the quietest places on earth.

5. Relation of measurement location and reverberation time

In order to better understand the diversity of the acoustical parameters in the LR2 and LY caves, additional charts with the order of measurement locations are shown in Figs. 13 and 14. The order starts counting from the entry of the particular cave with the number 1 and so on.

For both the LR2 and LY caves, the shortest reverberation time is observed next to their entrances. This is the result of the large amount of snow absorption that is always located in that area. The reverberation time of the last measured points (end of the cave) is lower than the median value. This is the result of frozen boulders or moraine. The diversity of results for the middle part of the caves is the result of the geometrical dimensions in those particular spots and the wall state or substance. As the size of each spot can be easily and quickly measured, the only unknown is the condition of the walls (icy or snowy, rough or smooth rocks, ground etc.). This provides an opportunity to estimate the state of the walls on the basis of the impulse response and basic geometrics. Therefore, reverse analysis of the acoustic absorption could lead to a fast and convenient way to monitor the changes and current state of glacier caves.

6. Summary and conclusions

The acoustical measurements of four different glacier caves in the Svalbard archipelago have shown the diversity of reverberation time and other acoustical parameters. All of the caves share a similar acoustical character in the proximity of the entrance, which is mostly made of snowy walls. The interior of the caves is very complex in geometry and surface texture and that results in different acoustical features. The reverberation time varies from 0.5 to 2 s for medium frequencies and up to 4 s for low ones. Early Decay Time values are generally lower than T10, T20 or T30. In comparison to the stone caves investigated in [5], the acoustics of glacier caves can be described in general as dry and intimate.

The performed calculations and analysis can be utilized while monitoring the morphology and state of the ice in a very fast and efficient way. The obtained results are to be a reference point for future activities in that field. The obtained spatial impulse responses can also be used in virtual reality systems or multimedia applications in order to recreate the character of this kind of unique space.

CRediT authorship contribution statement

Paweł Małecki: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Dorota Czopek:** Investigation, Data curation, Funding acquisition. **Janusz Piechowicz:** Investigation. **Jerzy Wiciak:** Conceptualization, Investigation, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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