Spectrum Analysis and Angle-of-Arrival Estimation Methods for Studying the Acoustics of Prehistoric Rock Painting Sites in Finland

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Key terms

Acoustics, echoes, reflections, reflectivity, archaeoacoustics, rock art landscapes, rock paintings, cliffs, ritual sites, Northern Europe, Finland, Lake District, prehistory, audio signal analysis, spectrum analysis, audio spectrum, angle-of-arrival calculation, angle of arrival, direction of arrival, impulse response measurement, oscillogram, spectrogram, sound pressure level plot, tetrahedron microphone array, condenser pressure microphone, deconvolution, cross correlation, excitation signal

Abstract

The article gives a full report of the sound analysis and visualization methods used for examining the acoustic characteristics of the echoes at prehistoric rock art sites in Finland. The methods developed in the University of Helsinki Music Research Laboratory are exemplified with previously unpublished data gathered mostly during the field season 2018 in the Lake District of southeastern Finland. The primary audio analysis method is multichannel impulse response measurement using a custom-designed tetrahedron microphone array and various types of excitation signals. The impulse responses are used for both analyzing the audio spectrum and angle of arrival of the echoes projected by the painted cliffs using custom-written signal analysis software.

1. Introduction

Over the last decades, the acoustics and auditory culture of the rock art sites from the past have become an increasingly popular theme for research worldwide. Researchers have studied acoustical properties and phenomena in various archaeological settings, such as caves, shelters, canyons and cliffs provided with painted or carved images (Reznikoff 1987a; 1987b; 1995; 2002; Reznikoff & Dauvois 1988; Waller 1993; 2006; Goldhahn 2002; Waller & Arsenault 2008; Díaz-Andreu & García Benito 2012; Mattioli & Díaz-Andreu 2017; Mattioli *et al.* 2017; Till *et al.* 2017). Whether obtained by subjective or objective, i.e., quantitative methods, the results of these studies tend to show a correlation between special acoustical effects and the placement of the images. The recurrent echoes or resonance or reverberation patterns suggest that sound played some role in the development and use of these sites, mainly associated with myths, beliefs and ritual activities.

In 2013, a joint musicological and archaeological research project was started to study the acoustical properties of the rock painting sites in Finland (Rainio *et al.* 2014; 2017). The Finnish rock paintings, made by prehistoric hunter-gatherers (5200–1000 BC), are typically situated on vertical cliffs or exposures of granitic bedrock that were worn smooth by glaciers (Kivikäs 2005; Seitsonen 2005; Lahelma 2008). As a rule, the cliffs face lakes, straits or other waterways and can only be accessed by water, in the summer, or over the frozen surface of the lake, in the winter. This means that the paintings, mainly depictions of elks, boats and anthropomorphs, must have been crafted from a boat or from ice (Seitsonen 2005: 7). To study the acoustics of these hardly accessible, special places, new audio analysis and field recording methods were developed. The primary analysis method is multichannel impulse response measurement using a custom-designed microphone array and custom-written signal analysis software. The method enables detailed analysis of the audio spectrum and estimation of the angle of arrival of the echoes projected by the cliffs. The measurements conducted at two Finnish rock painting sites between 2013 and 2014 show that these sites are highly reflective, capable of creating strong, discrete echoes that emanate from the painted cliffs or even directly from the paintings (Rainio *et al.* 2014; 2017). Consequently, the echoes form a special acoustic environment distinct from the nearby surroundings.

This article gives a full report of the spectrum analysis and angle-of-arrival estimation methods developed in the University of Helsinki Music Research Laboratory and used in the ongoing project (cf. Lassfolk & Uimonen 2008). The article evaluates their accuracy, limitations and suitability for studying different type of acoustic spaces. The methods are exemplified with previously unpublished audio data gathered at seven Finnish rock painting sites during the field seasons 2013–2014 and 2018. The new, larger body of data provides a more accurate and generally applicable picture of the echoes at Finnish rock painting sites, and helps to assess their distinctive acoustical characteristics in different seasons and conditions, and in comparison to other echoes heard in the lake environment. “What is so special about those echoes at rock paintings?” “Aren’t there echoes to be heard almost everywhere?“ These are repeated questions posed to us in scientific conferences, seminars and other events. At this stage of the project, we might have enough information to answer these questions.

2. Research Locations

Up to the present, our team has conducted acoustical measurements at seven rock painting sites in Finland, both in northern and southern parts of the country. The measurements at the sites of Värikallio and Julma-Ölkky, situated in the northeastern wilderness area, were carried out between 2013 and 2014 and published in 2014 and 2017 (Rainio *et al.* 2014; 2017). The measurements at the sites of Siliävuori, Myllylampi, Verla, Löppösenluola and Verijärvi, situated in the southeastern Lake District, were carried out in 2018. The results of these latter measurements will be published here for the first time and compared with the results of the earlier measurements.

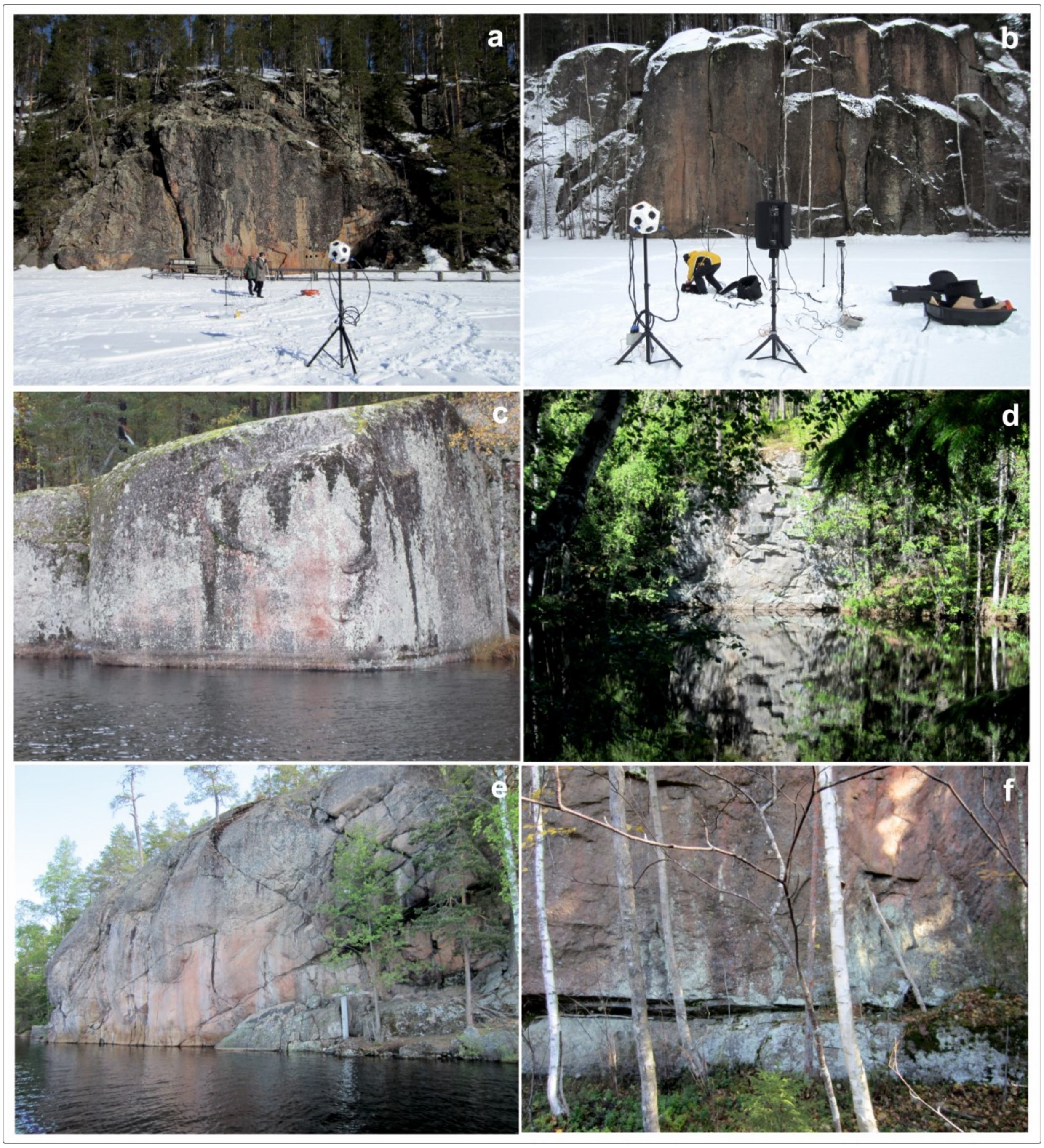

Figure 1: Rock painting sites of a) Värikallio, b) Siliävuori, c) Verla, d) Verijärvi, e) Löppösenluola and f) Myllylampi. Photographs: Riitta Rainio.

In terms of acoustical characteristics, the rock painting sites of Värikallio, Julma-Ölkky, Siliävuori and Verla can be regarded as well-preserved. The painted cliffs have outstandingly smooth and even surfaces that rise directly from a lake to a height of 4–17 m (Figs. 1a, 1b, 1c, Table 1). At all sites, the wall-like surfaces tilt towards the lake at an angle of 92–100^0, protecting the paintings from rain, snow and vegetation. The painted figures lie between 0.2 m and 2.5 m above the waterline, i.e., within reach of a person sitting or standing in a boat or on ice (Kivikäs 1995: 289, 298, 300, 303; Miettinen 2000: 114; Lahelma 2008: 228, 267). This indicates that the water levels, and thus the acoustics of the surrounding sites, have not changed notably since the paintings were made. The highest figure at Siliävuori, an outline elk at a height of 3 m, was probably made before a slight drop in the lake level, but a stylistically younger stick-figure elk at a lower level indicates that the site was painted on several occasions (pers. comm. Antti Lahelma; see also Miettinen 1992: 23–33). Also at Verla and Värikallio, figures at different elevations, red stains in different hues and overlapping strokes suggest that the painting tradition lasted for a time (Miettinen 1990: 64; 2000: 114–118; Kivikäs 2005: 31). At Julma-Ölkky, where there are only a few images, the tradition might have been more short-lived. With the exception of the spectator pier built in front of the Värikallio painting, the sites of Värikallio, Julma-Ölkky and Siliävuori have remained in their natural state and provide an opportunity to experience the rocky lake landscape more or less as it was in prehistoric times. Judging from pollen analyses (e.g. Alenius *et al.* 2009; 2013), differences in vegetation were not remarkable enough to have an effect on the acoustics. However, the site of Verla has been encircled by several historical buildings, the reflections of which must be recognized in the impulse responses and filtered out.

Table 1: Measurements and other characteristics of the studied rock painting sites.

	Väri-kallio	**Siliä-vuori**	**Julma-Ölkky**	**Verla**	**Veri-järvi**	**Löppösen-luola**	**Mylly-lampi**
Width & height of the cliff wall (m)	15 x 12	10 x 17	25 x 17	8 x 4	8 x 8	26 x 14	~10 x 12
Maximum tilt of the cliff wall	100°	97°	100°	92°	94°	116°	92°
Distance to the opposite shore (m)	110	112	–	44	44	320	–
Maximum width of the panel (m)	10.5	10	1	6	8 *	18 *	1
Height of the panel above lake level (m)	0.2–2.5	1.8–3	1.25–1.5	0.5–2.1	1.4–2.5	2.3–4	4
Number of the painted figures	>60	>10	3–4	>12	>4	>2	>3
Sources	Miettinen 1992: 23–33; 2000: 112–125, 136–138; Kivikäs 1995: 289–290, 298, 300, 303, 307; Lahelma 2008: 228, 243, 246, 267; our own fieldwork 2013, 2014, 2018.						
	*) Supposed original width of the panel						

In terms of acoustics, the rock painting sites of Verijärvi, Löppösenluola and Myllylampi are less well-preserved or partly destroyed. At Verijärvi, the painted cliff is heavily fractured, rugged and uneven (Fig. 1d). As separate blocks of stone can be lifted from the bottom of the nearby lake, it appears that large parts of the cliff's surface have collapsed into the lake, carrying away most of the original painting (Kivikäs 2005: 9). Remaining figures can be found on both margins of the cliff, at a height of 1.4–2.5 m from water (Kivikäs 1995: 307; Lahelma 2008: 246). At Löppösenluola and Myllylampi, the images, only few in number, are situated 2.3–4 m above water (Figs. 1e, 1f) (Kivikäs 1995: 289, 305; Miettinen 2000: 136–137). This indicates that the water levels of these lakes have dropped a couple of meters, exposing rock shelves and other irregularities at the foot of the cliffs, as well as strips of land. A drop of that size is not much, but in consequence, the shoreline at Myllylampi has receded into a distance of 70 m and trees have grown in front of the cliff (Lahelma 2008: 243). Thus, the environment has undergone great changes. These changed acoustical environments are worth studying, because they allow us to contrast well-preserved cliffs with cliffs that have lost their highly reflective, smooth and bare surfaces. Furthermore, echoes from the altered cliffs can be compared with echoes captured at random reference points in the more distant surroundings of the rock paintings.

3. Methodology

3.1 Fieldwork equipment

The principal research method is impulse response measurement (e.g. Stan *et. al.* 2002) applied for analyzing the temporal and spectral characteristics of the sites as well as for estimating the angle of arrival of discrete echoes from reflecting surfaces such as the painted cliffs. The impulse responses are recorded at the sites with a custom-designed microphone array and the analyses are made using the Spectutils Signal Analysis and Visualization Toolkit (Lassfolk & Uimonen 2008) as well as custom-written software for the GNU Octave Scientific Programming Language. Impulse response data is also collected for future auralization purposes using directional microphone systems.

The fieldwork equipment were designed for use in roadless wilderness in both summer and winter weather conditions. Thus, much effort was used to keep the amount and weight to a minimum while still providing high sound quality and a wide selection of excitation signals. The core device of the fieldwork equipment is a tetrahedron microphone array installed in a custom-built microphone stand. The array consists of four Neumann KM 183 condenser pressure microphones with 40 cm distance between capsules. Designed for diffuse field recordings, the KM 183 microphone capsules are pointed upwards to gain a maximally flat frequency response on the horizontal plane. The tetrahedron array is oriented so that three of the microphones form a triangle on the horizontal plane while the fourth is directly above of the center of the triangle (see Fig. 3). A Zoom F8 8-channel portable digital audio recorder is used as the recording device. All recordings are made with a 96 kHz sampling rate and with 24 bits per sample resolution.

The excitation signals consist of both synthesized and acoustic signals and are chosen according to the logistical and weather conditions at the sites. The synthesized signal set consists of 10 second and 30 second logarithmic sine sweeps from both 20 to 20000 Hz and 200 to 10000 Hz, a series of fixed-frequency sine chirps, noise bursts, unit impulses and recorded human voice. 40 cm diameter balloon pops are used as complementary excitation signals and as primary excitation signals when access to the site requires the amount of equipment to be kept to a minimum.

As the sound source for the synthesized signals, a custom-built omnidirectional dodecahedron loudspeaker driven by a JBL Class-D car audio amplifier is used with a 12 V motorcycle battery as the power source. A Zoom H4n portable audio recorder is used as the playback device. The stand-mounted loudspeaker requires a steady surface. While wintertime recordings can be made on ice (Fig. 2a), summertime recordings impose some challenges (Fig. 2b). For summer season recordings on water, we use a custom-build raft to carry the loudspeaker and microphone array positioned 2.5 m apart from each other. On ice, or when making the recording from the opposite shore of an especially narrow lake, the distance between the excitation signal and the microphone array is 5 or 10 m, depending on the circumstances in the field. Either way, the microphone array is always positioned directly between the loudspeaker and the studied painted cliff. The position of the microphone array is documented with a RTK GPS or a Garmin handheld GPS, a Leica laser distance meter and a Suunto optical sighting compass, the precision of which is 0.5 °.

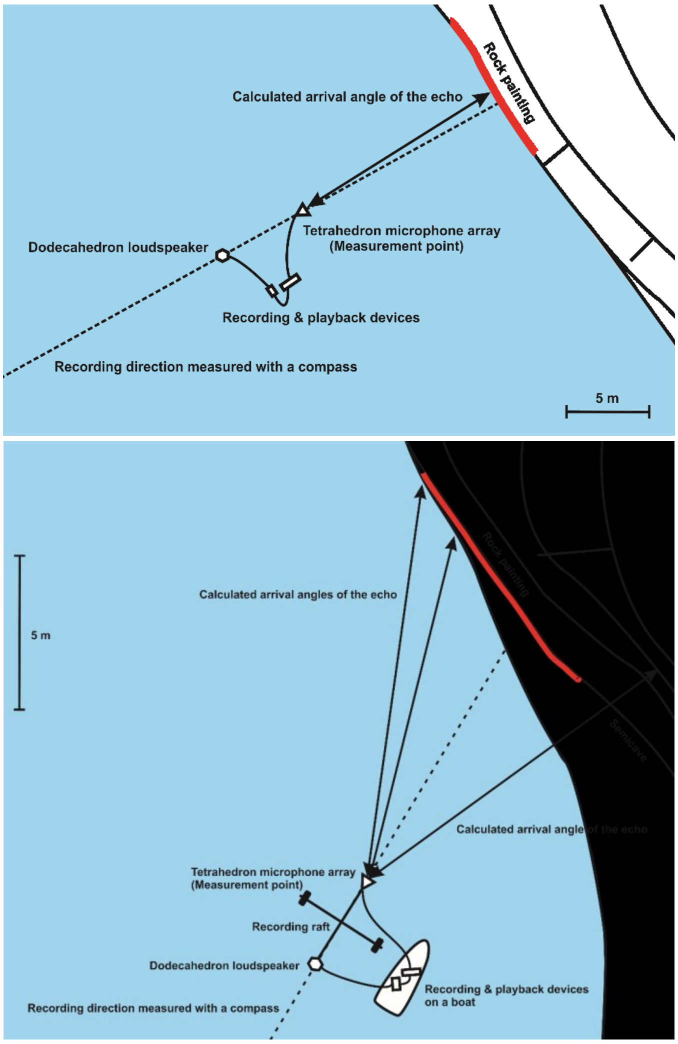

Figure 2: Recording setup a) on ice at the rock painting site of Siliävuori and b) on water at the rock painting site of Löppösenluola. Drawings: Riitta Rainio.

In addition to the spectrum and angle-of-arrival estimation measurements, a parallel set of recording equipment is used for auralization purposes. Both a Sennheiser Ambeo VR Ambisonics microphone and a custom-built 6-channel directional microphone array are currently being tested. The recordings are made for future listening tests and audio-visual virtual reality renderings of the sites. Topographic 3D models of the sites of Värikallio, Julma-Ölkky and Siliävuori were created using a Leica ScanStation 2 laser scanner.

3.2 Analysis tools and methods

Before analysis, the recorded 4-channel sine sweeps are deconvolved (see Farina 2000) to yield the impulse response of the measurement point. The impulses, i.e., either deconvolved sine sweeps or recorded balloon pops, are analyzed using both standard audio signal analysis methods as well as angle-of-arrival estimation.

In the analysis phase, the recorded echoes are visually compared with the excitation signals as well as with signals recorded at nearby reference points and at other research sites. Comparisons are made with oscillograms for temporal characteristics and spectrograms for spectral characteristics. Also, amplitude versus time plots are used for illustrating temporal changes in peak amplitude levels. After this, the strongest echo signals are processed with the automatic angle-of-arrival estimation algorithm. Our hypothesis is that an echo, outside the Haas effect time window and with a strong temporal and spectral similarity to the excitation signal, produces a phantom sound source that can be localized in the acoustic space and produces a recognizable reproduction of the excitation signal.

Angle-of-arrival estimation is based on the arrival time differences between the capsules in the tetrahedron array. The horizontal and vertical, i.e., azimuth and elevation angles are resolved by applying inter-channel cross correlation and trigonometry. The 4-channel synchronized deconvolution and estimation process is performed with custom Octave software. The process for analyzing a sine sweep excitation signal is illustrated in Fig. 3. There, the recorded 4-channel sine sweep is first processed with a frequency domain deconvolution method introduced by Farina (2000) (Stage 1) by using the excitation sine sweep as a reference signal. The resulting impulse response is cross-correlated between the signal channels (Stage 2) to find the arrival time differences between microphone signals for the impulse, i.e., the recorded excitation signal or echoes emanating from reflecting surfaces. Based on the inter-microphone time difference data and the distance between capsules, the angle of arrival is calculated (Stage 3) by applying the trigonometric function in Equation 1.

$$\theta = \cos^{-1}\left(\frac{\Delta t_{AB}}{\Delta t_{MAX}}\right) \tag{1}$$

The angle of arrival is calculated from the arrival time difference (Δt_{AB}) between two measurement points A and B relative to the maximum time difference (Δt_{MAX}) between the points determined by their relative distance and the speed of sound. The measurement algorithm chooses a pair of microphones from the horizontal plane as the measurement points to find the azimuth angle. The vertical angle is calculated by using the top microphone, the mean arrival time of the horizontal microphone triangle and the distance from their center point. While the distance between microphone capsules is a constant value of 40 cm as well as the distance between the top microphone and the center point of the horizontal plane of the tetrahedron, the speed of sound is a variable and adjusted according to the conditions at the site. The angle-of-arrival values are finally proportioned to the measured recording direction in the field and then normalized to the global coordinate system, taking into account a local magnetic declination.

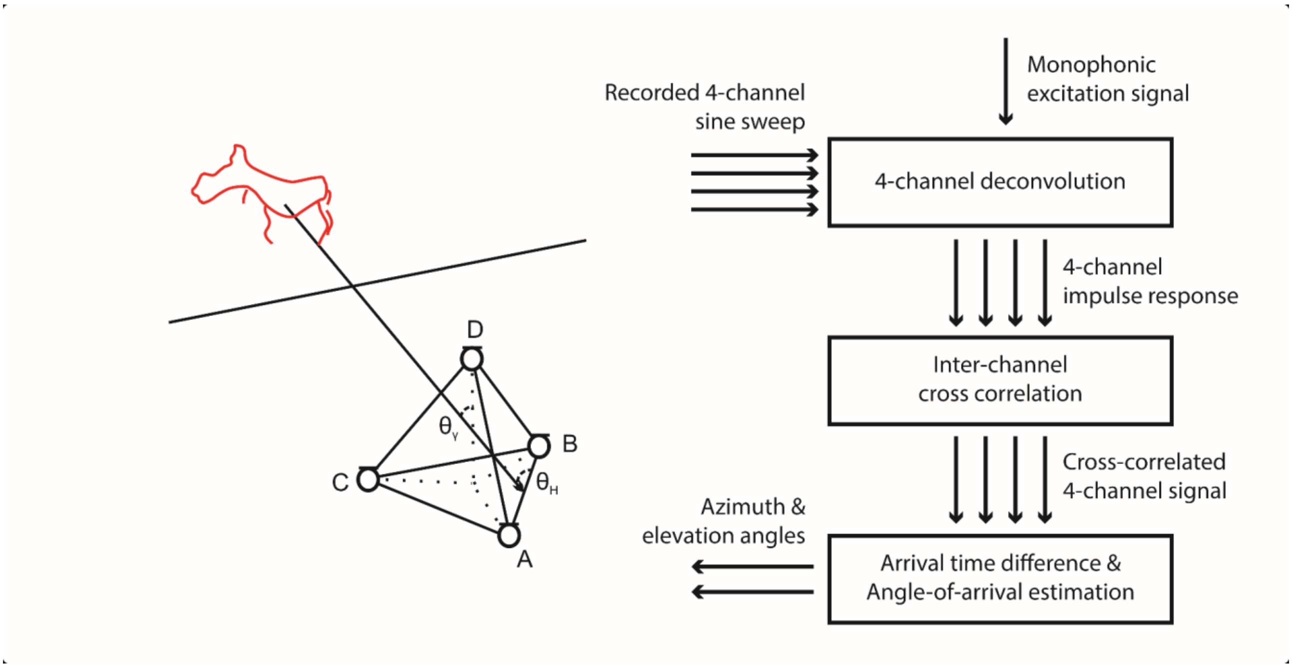

Figure 3: The angle-of-arrival calculation process for sine sweep signals. Drawing: Kai Lassfolk.

The signal analysis plots in the Results chapter were done with the Spectutils functions oscgram(), amp2dt() and spec3dw(). The oscgram function plots an oscillogram, i.e., the variation of air pressure versus time (see Fig. 10). The amp2dt function, as used in this text, plots the time-varying peak amplitude level in decibels (see Figs. 4, 5, 7, 8, 9). Spec3dw plots 3D magnitude spectrograms obtained by short-time Fourier analysis (see Fig. 6). In the Figures, the echo of the painted cliff is marked with letter “E” while other echoes, e.g., from the opposite shore are marked with an “O”.

4. Results

4.1 Echoes at rock paintings versus echoes at reference points

All the rock painting sites studied so far have a discrete echo projecting from the direction of the painted cliff. At the well-preserved sites of Siliävuori, Verla, Värikallio and Julma-Ölkky, this echo is a fairly accurate copy of the given excitation signal and differs clearly from the rest of the reflections seen in the spectrum analysis plots (Figs. 4a, 5a, 8a). The sound pressure level of the echo is relatively high, -23–25 dB at a distance of 44 m from the painted rock, and -12 dB at a distance of 12 m. The decay of the echo is sharp and abrupt, and not gradual as in most other reflections. Furthermore, a broad range of frequencies is heard in the echo, even in a distance of 44 m from the reflecting surface (Figs. 6a, 6b). These characteristics are due to the smoothness, evenness and large area of the painted rock wall, the fact that a large amount of energy is reflected back exactly at the same time. The surface of the lake does not seem to have a noticeable effect on the echoing, but causes an empty gap, a totally soundless moment, between the excitation signal and the echo from the rock painting (see especially Figs. 4a, 4b, 6b). The only reflection in the plots that is somehow comparable to the rock painting echo, is generated by a modern building on the opposite shore of the Verla rock painting (see Fig. 5a). However, this echo is weaker in intensity as the reflecting surface is much closer to the microphones.

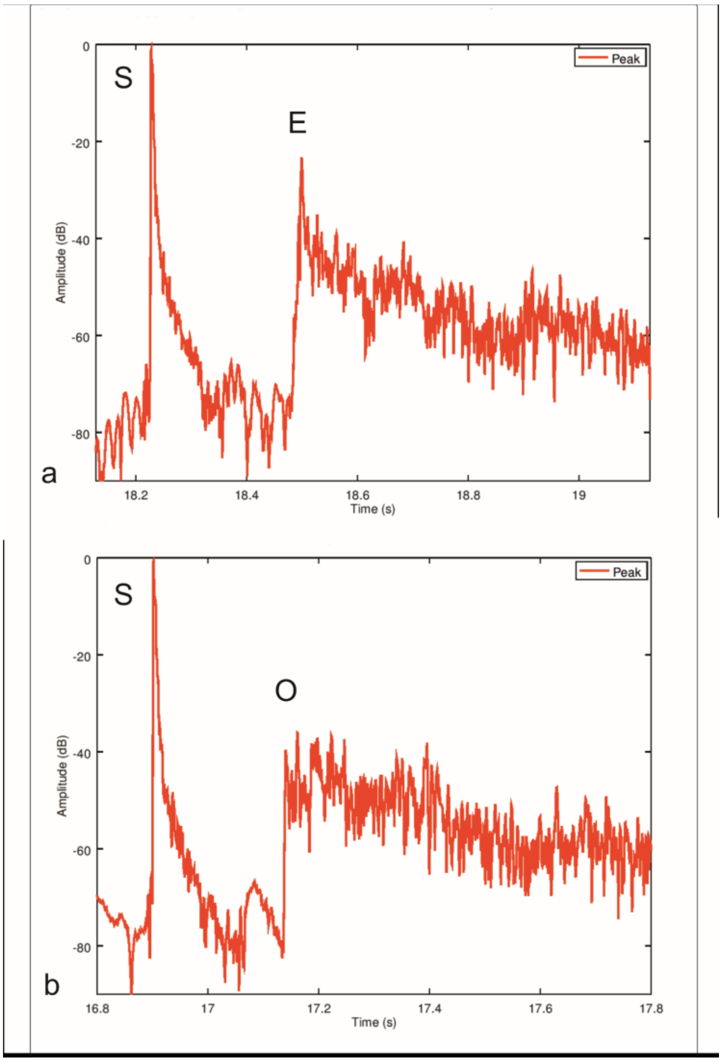

Figure 4: Unweighted peak sound pressure level plots showing the impulse response a) at the rock painting site of Siliävuori (measurement point on ice 44 m off the painted cliff, excitation signal balloon pop 10 m off the microphones, temperature -12° C) and b) at a reference point by the same lake (measurement point on ice 39 m off the shore, excitation signal balloon pop 10 m off the microphones, temperature -12° C). S = excitation signal, E = echo from the painted cliff, O = other echo.

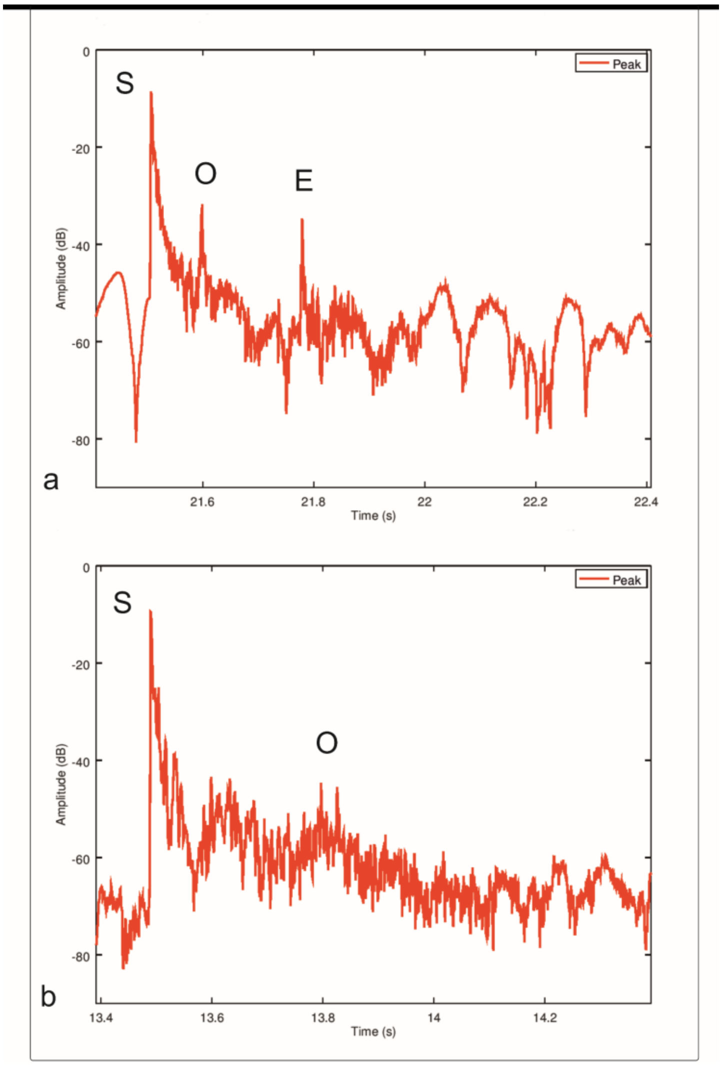

Figure 5: Unweighted peak sound pressure level plots showing the impulse response a) at the rock painting site of Verla (measurement point on the opposite shore 44 m off the painted cliff, excitation signal balloon pop 6.6 m off the microphones, temperature +0° C) and b) at a reference point by the same lake (measurement point on the shore, excitation signal balloon pop 6.6 m off the microphones, temperature +0° C). S = excitation signal, E = echo from the painted cliff, O = other echo.

All reference points by the same lakes have discrete echoes projecting from rocky and wooded terrain on the nearest shore. These echoes, captured 45–50 m aside from the rock paintings, are clearly different from the echoes described above (Figs. 4b, 5b). The sound pressure level of these echoes is generally lower, the frequency range narrower and the decay prolonged and intermingled with the general reverberant tail. The sharp, abruptly decaying spike, typical of the rock painting echoes, is missing from the plots. These characteristics are due to the rugged surfaces, rocks or trees, that diffuse the incoming sound energy and create a countless number of reflections returning in rapid succession.

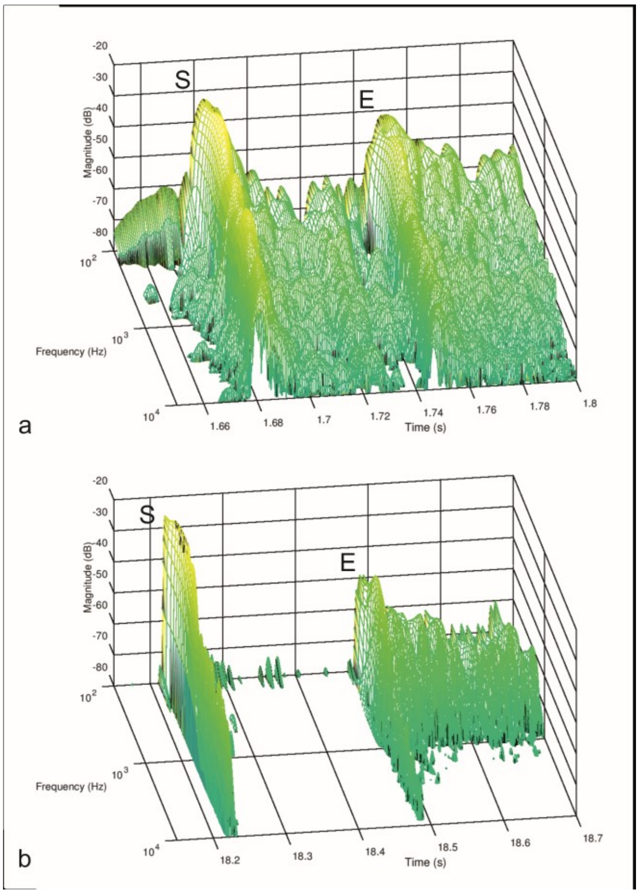

Figure 6: 3D spectrograms showing the impulse response at the rock painting sites of a) Värikallio (measurement point on ice 12 m off the painted cliff, excitation signal sine sweep 10 m off the microphones, temperature +2° C) and b) Siliävuori (measurement point on ice 44 m off the painted cliff, excitation signal balloon pop 10 m off the microphones, temperature -12°). S = excitation signal, E = echo from the painted cliff.

4.2 Echoes in winter versus summer

The impulse responses captured at the same rock painting site in different seasons are highly similar. As seen in the sound pressure plots from Siliävuori, there are no big differences in the shape of the echo between the winter-time and summer-time recordings performed on lake ice and open water, respectively (Figs. 7a, 7b). One of the differences is that in the summer-time recordings, the empty gap between the excitation signal and the echo from the rock painting is provided with some early reflections, probably caused by the boat and the raft accommodating the recording equipment. In addition, open water might be a more reflective surface than lake ice usually covered by snow. On the basis of these plots, the layer of snow absorbs sound effectively. Another difference is that the sound pressure level of the rock painting echo is somewhat lower in the summer-time recordings. The reason for this remains unclear, because there are no trees in leaf veiling the rock painting and so the rock wall is similar all through the year. In winter, it is always free of snow. Lastly, other echoes at the site, mostly projecting from the opposite shore of the lake, are more discernible in summer than in winter. This is easily explainable, because the rugged terrain causing these echoes is covered by deep snow during the winter months.

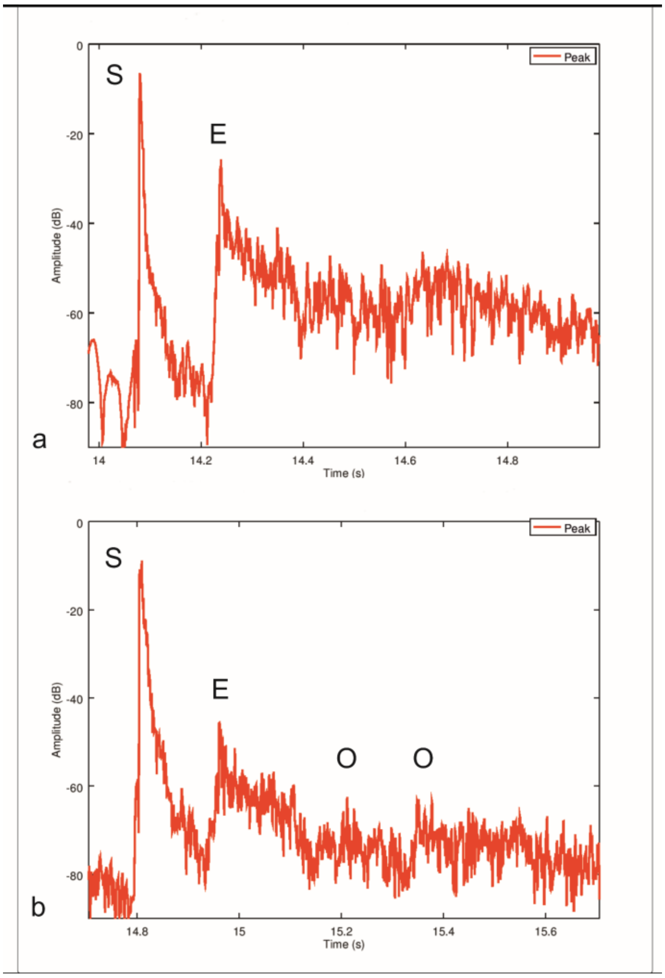

Figure 7: Unweighted peak sound pressure level plots showing the impulse response at the rock painting site of Siliävuori a) in winter (measurement point on ice 26 m off the painted cliff, excitation signal balloon pop 10 m off the microphones, temperature -12° C) and b) in summer (measurement point on water 26 m off the painted cliff, excitation signal balloon pop 2.5 m off the microphones, temperature +5° C). S = excitation signal, E = echo from the painted cliff, O = other echo.

4.3 Echoes at well-preserved sites versus echoes at partly destroyed sites

As noted above, the rock painting sites of Siliävuori, Verla, Värikallio and Julma-Ölkky feature an accurate, strong echo that appears to be characteristic of the well-preserved sites (Figs. 8a, 10a, 10c, 10e). Less well-preserved or partly destroyed sites feature another type of echoes. At the sites of Löppösenluola, Myllylampi and Verijärvi, the echo projecting from the direction of the rock painting dominates the impulse response, but its peak level is remarkably weaker than the echo at the well-preserved sites (Figs. 8b, 9a, 9b). The peak level of this weak echo is -27 dB at a distance of 12 m from the painted rock, and -39–41 dB at a distance of 44 m. Instead of the abrupt decay described above, this echo has several successive intensity peaks, clearly seen in the oscillograms (Figs. 10b, 10d, 10f). Although at Myllylampi and Verijärvi the envelope of the excitation signal has a relatively long decay – due to the trees in the vicinity of the measurement point – the series of successive peaks in the echo appear to result from the reflecting rock wall. These diffused echoes are probably caused by the fractures and irregularities on the broken and otherwise altered painted rocks. Thus, their characteristics might be regarded as the distinctive features of the weathered and acoustically distorted rock painting sites. As such, these echoes are indistinguishable from common echoes heard in rugged terrain and lake environment. In the case of Myllylampi, the majority of the reflections in the plots are caused by the trees veiling the painted rock.

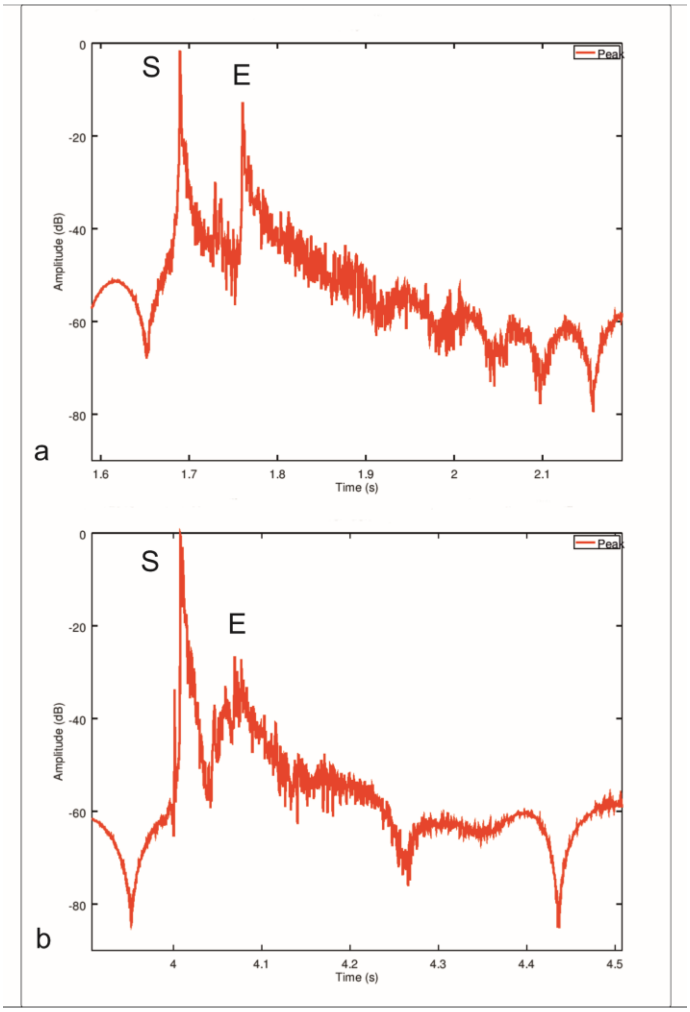

Figure 8: Unweighted peak sound pressure level plots showing the impulse response at the rock painting sites of a) Värikallio (measurement point on ice 12 m off the painted cliff, excitation signal sine sweep 10 m off the microphones, temperature +2° C) and b) Löppösenluola (measurement point on water 12 m off the painted cliff, excitation signal sine sweep 2.5 m off the microphones, temperature +12° C). S = excitation signal, E = echo from the painted cliff.

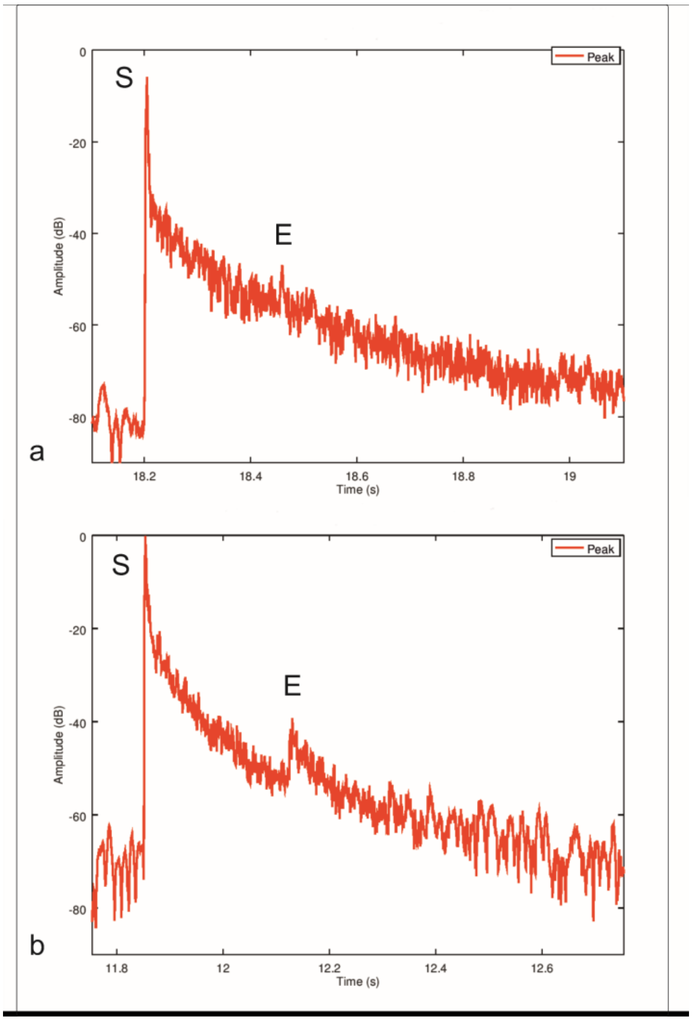

Figure 9: Unweighted peak sound pressure level plots showing the impulse response at the rock painting sites of a) Myllylampi (measurement point on bog 44 m off the painted cliff, excitation signal balloon pop 5 m off the microphones, temperature +12° C) and b) Verijärvi (measurement point on the opposite shore 44 m off the painted cliff, excitation signal balloon pop 5 m off the microphones, temperature +15° C). S = excitation signal, E = echo from the painted cliff.

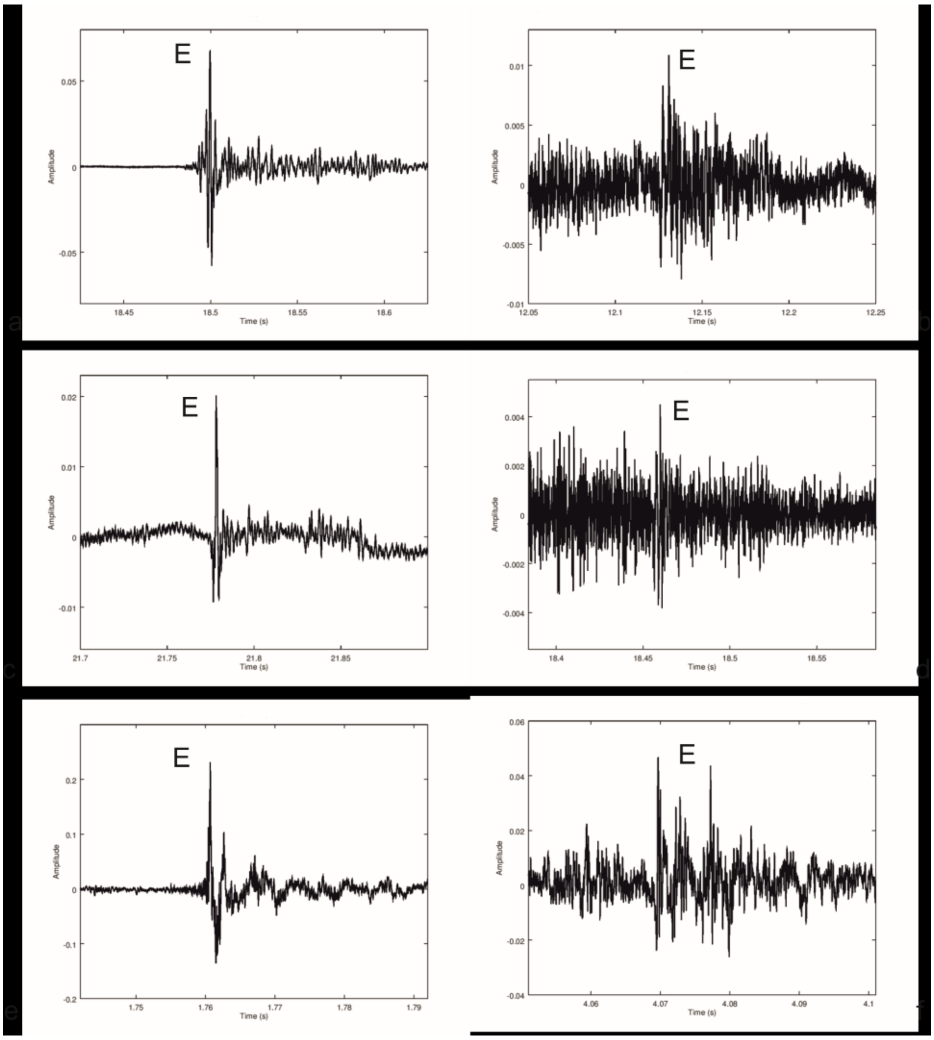

Figure 10: Oscillograms showing the echo from the painted cliff at the rock painting sites of a) Siliävuori (measurement point on ice 44 m off the painted cliff, excitation signal balloon pop 10 m off the microphones, temperature -12° C), b) Verijärvi (measurement point on the opposite shore 44 m off the painted cliff, excitation signal balloon pop 5 m off the microphones, temperature +15° C), c) Verla (measurement point on the opposite shore 44 m off the painted cliff, excitation signal balloon pop 6.6 m off the microphones, temperature +0° C), d) Myllylampi (measurement point on bog 44 m off the painted cliff, excitation signal balloon pop 5 m off the microphones, temperature +12° C), e) Värikallio (measurement point on ice 12 m off the painted cliff, excitation signal sine sweep 10 m off the microphones, temperature +2° C), f) Löppösenluola (measurement point on water 12 m off the painted cliff, excitation signal sine sweep 2.5 m off the microphones, temperature +12° C). E = echo from the painted cliff.

4.4 Angle-of-arrival estimations

Our angle-of-arrival estimations show that all seven rock painting sites studied so far have an echo that projects from the direction of the painted cliff. The echo occurs both in connection with the well-preserved and altered cliffs, and appears to be a fundamental characteristic of a rock surface of this size. The calculation of the azimuth produces invariably an arrival angle that points to the painted area of the cliff or an area showing traces of faded images. This panel is usually between 6 and 10 m in breadth. At the well-preserved sites of Siliävuori, Verla, Värikallio and Julma-Ölkky, the direction of arrival of the echo is unambiguous (see Fig. 2a). At Löppösenluola and Verijärvi, it is possible to calculate separate, slightly deviating arrival angles for the peaks of the diffuse echo (see Fig. 2b). This suggests that these separate, rapidly following reflections project from different parts or facets of the cliff.

The calculation of the elevation angle produces two kinds of results. At Värikallio and Siliävuori, the calculated angles point to the heights of 2.5 and 1.5–3 m on the rock wall, i.e., to the level of the paintings (Fig. 11). However, at Julma-Ölkky, the calculated angles point to a height of 6.5–7.6 m, i.e., far above the paintings (Fig. 12). This same height recurs at three different measurement points at Julma-Ölkky, situated at distances of 16, 37 and 78 m from the painted cliff. These results indicate that at some sites the echo arrives from the level of the paintings, while at others not. Furthermore, the results raise the question, whether this characteristic had an influence on the number of the images and the intensity and length of the painting tradition. For some reason, at least, the large, smooth and imposing cliff of Julma-Ölkky features only a couple of images.

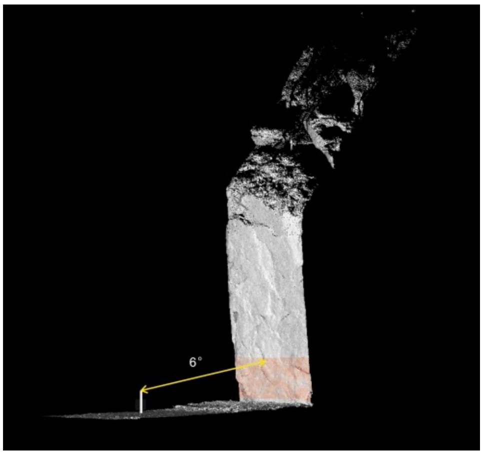

Figure 11: Still picture of the 3D model showing the painted cliff of Värikallio, the painted area (in red) and the elevation angle of the echo (measurement point on ice 12 m off the cliff, excitation signal sine sweep 10 m off the microphones, temperature +2° C). Still picture: Jari Okkonen.

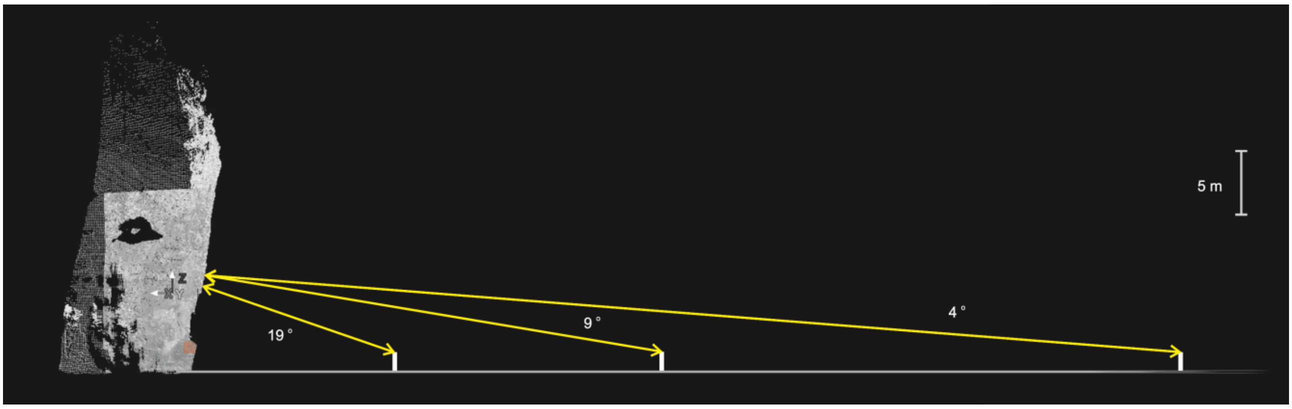

Figure 12: Still picture of the 3D model showing the painted cliff of Julma-Ölkky, the painted area (in red) and the elevation angle of the echo at three measurement points (measurement points on ice 16, 37 and 78 m off the cliff, excitation signal sine sweep 10 m off the microphones, temperature -13° C). Still picture: Jari Okkonen.

While the angle-of-arrival estimation manages to calculate constant directions for the echoes from the rock paintings, the situation is less satisfactory with other echoes heard at the sites. These echoes arriving after the rock painting echo often overlap, coincide and intermingle with a number of reflections and thus produce random results in the estimation.

5. Discussion

On the basis of our research, it is clear that the echoes in the Finnish environment, especially by lakes and rocky terrain, are not all similar with each other. The signal analysis and angle-of-arrival estimation methods applied by us show remarkable differences related to intensity, duration and frequency spectrum of the echoes, as well as to the unambiguity and accuracy of their direction of arrival. Highly reflective, smooth rock walls, including those provided with prehistoric paintings, produce strong and sharp echoes with an abrupt decay, a broad frequency spectrum and unambiguous direction of arrival. These echoes repeat the given excitation signal accurately, almost as it is. Irregular, fractured rock walls, like those at the altered rock painting sites or almost all reference points, produce softer and longer echoes, in which the decay is gradual and the direction of arrival more vague. These echoes modify the given signal, giving it a somewhat distorted audible shape. Thus, it is possible to state that the rock painting sites in Finland have a special, characteristic echo that is different from most of the echoes or reflections in the environment. The sites can also be said to have special acoustics, even though the number of audible echoes is often only one or two, reverberation time moderate and other acoustic parameters within the "normal" range (cf. criteria for "special acoustics" in Reznikoff 2002; Díaz-Andreu & García Benito 2012; Till *et al.* 2017). These type of sites with a highly reflective wall on the water's edge are acoustically exceptional and should be studied on their own terms. In addition to the reflective wall, an extraordinary and integral part of the sites' acoustics is the soundless gap between the signal and the echo, caused by the open surface of the lake. It makes the signal – as well as its reflection – sound very dry, "empty and dreary". This type of acoustics, a combination of dry and resounding components should be well-suited to sound rituals that use repetitive, impulse-like signals: clapping, drumming or reciting. It should be less suitable to long, sustained notes, like in singing.

Our method for angle-of-arrival estimation is applicable to open spaces resembling the Finnish rock painting sites that have a single discrete echo and a minimum of other overlapping reflections. The method is less efficient to analyzing diffuse or flutter echoes, and dysfunctional in caves, semicaves and other enclosed spaces. To minimize disturbances caused by other reflections, gusts of wind and measuring inaccuracies in the field, the tetrahedron microphone array should be located rather close to the studied reflecting surface, at a distance of 10–50 m. This ensures that the echo to be estimated is distinct enough, and that the reflecting surface takes up a relatively large sector in the visual field of 360 °. Based on the use of robust, general purpose pressure condenser microphones, the tetrahedron array has proven to provide high quality recordings even in wintertime, when the temperature is well beyond -10 ° C. However, despite the relative insensitivity to wind by pressure microphones and the use of custom-built wind shields, the recordings have to be made at relative calm wind conditions. Directional microphones, used for auralization purposes, are even more sensitive in this regard. Therefore, the measurements are typically made at daybreak and only when the local weather forecast is positive. Moreover, logistical conditions and the terrain at the sites often force to limit the amount and placement of the equipment. Therefore, several fieldwork trips have been carried out at the same sites to gather comparable research data.

6. Conclusions

On the basis of our acoustical measurements at seven research locations, the rock painting sites in Finland produce a discrete echo projecting directly from the painted cliffs facing lakes or other bodies of water. Smooth, well-preserved cliffs project a sharp, accurate copy of the excitation signal, whereas fractured, less well-preserved cliffs produce a distorted version of it, an echo that resembles more the echoes at random reference points by the same lakes. The echoes from the painted cliffs are distinctly localizable, sometimes directly in the paintings, sometimes higher up on the cliff walls. The cycles of the seasons do not seem to have a notable effect on the echoing. The audio analysis and angle-of-arrival estimation methods, developed for this project, appear to be well-suited to the studied type of acoustic spaces with one discrete echo and a minimum of other reflections. The methods are also robust in that they produce unambiguous and consistent results. However, to validate the comparison between different rock painting sites, the data should be gathered in exactly similar fieldwork conditions. On the lakes and in rugged landscapes, this is a continual challenge.

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