4450 words

Submission to American Indian Rock Art

ARARA 1998 Ridgecrest conference presentation

(Title)

Digital Acoustic Recording Techniques Applied to Rock Art Sites

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(Abstract)

This report describes the first application of digital recording techniques at rock art sites using professional acoustical apparatus and techniques. The digitized data from two sites near Phoenix, Arizona confirm earlier findings of echoes and/or back-scattering of sound waves at sites associated with rock art. It is anticipated that the increased information content from such digitized analyses may help resolve questions regarding the relevance of acoustics to the study of rock art.

INTRODUCTION

The presence of echoing has been noticed at numerous rock art sites (Steinbring 1992; Waller 1993a). Echoes have been documented with sound level measurements by analog techniques (Waller 1993b), providing a body of evidence for the potential importance of acoustics to the study of rock art. These observations provided the impetus to conduct the present study according to state-of-the-art professional techniques using calibrated digital equipment.

(This paper is written in a manner intended to introduce rock art researchers to some important basic concepts of acoustics. A glossary appears in the Appendix for terms shown in quotes when first mentioned. For a more in-depth general background, see Pierce 1989.)

The law of conservation of energy can be invoked for the sound energy impinging on a rock surface. An "echo" occurs when sound reflects back to the listener from rocks or other hard surfaces, especially flat vertical surfaces. Closely spaced multiple echoes occur when a subsequent echo begins before the previous echo has ended. Closely spaced echoes may not be resolvable by measurements or by the human ear, while overlapping echoes cannot be resolved by measurements or ears. When echoes overlap in time, or when multiple echoes are so closely spaced in time that human ears cannot resolve individual echoes, the effect is called "reverberation". Reverberation is defined as the persistence of sound in a closed, or partially enclosed space after the source of sound has stopped (ASTM 1997). "Scattering" is a name given to the large number of mostly low energy sound reflections from small or irregular hard surfaces. The sum of the sound energies reflected, scattered, absorbed, and transmitted through the rock must equal the impinging energy. The sound energy "reflection coefficient" of a surface is a number ranging from zero to one. If, in addition to being hard and nonporous, a rock surface is also large and smooth, nearly all impinging sound energy is reflected and little is scattered: the reflection coefficient is nearly one.

Broadly speaking, two acoustical conditions are necessary for human listeners with normal hearing to perceive an echo. First, the echo strength must be sufficiently above the ambient noise level in a portion of the frequency range of human hearing. Second, the echo time delay must be sufficient to avoid "temporal masking" ("Haas effect") by the loud sound source: the echo must arrive 30-60 ms (milliseconds) or more after the noise stimulus has stopped. The short end of this range may be acceptable if the echo is strong. The long end of this range may be needed if the echo is weak. If temporal masking renders the echo inaudible, interesting acoustical effects may be noted, but they will not be perceived as a distinct echo.

How far must the listener stand from a rock art site to perceive a simple echo? The speed of sound is about 343 meters per second (1125 feet per second) at typical temperatures and atmospheric pressures. For a round trip echo delay of 30-60 ms, the listener must stand at least 5-10 meters (17-34 feet) distant from a reflecting surface. Simple echoes from that surface cannot be perceived if the listener stands too much closer. It is mentioned in passing that complex echoes involving multiple reflections also occur. Multiple reflections increase time delay, but change the echo's perceived "Direction Of Arrival (DOA)" as well. At this early time in acoustical rock art research, echoes perceived as arriving directly from the rock art itself are the primary focus of attention.

The acoustics of rock art sites can be studied and characterized by adapting the methods of architectural acoustics. The central idea is to consider the measurement space to be a linear system and characterize its "impulse response". Determination of the impulse response is the key objective.

METHODS

Site Selection And Description

The following criteria were used to select sites for the first tests of digital acoustic recording at rock art locations:

- minimum of modern alterations that may have affected acoustical properties
- minimum of ambient noise to interfere with data analysis
- quick and easy access to maximize time available for testing and minimize equipment transport
- representative of a variety of topology (hillside, canyon)
- recognized authenticity of the art

The sites selected are in the greater Phoenix, Arizona area and consisted of:

1) Hedgepeth Hills at the Deer Valley Rock Art Center. This site consists of a row of hillsides covered with a tumble of basalt rocks (roughly similar in appearance to sections of the escarpment at Petroglyph National Monument in Albuquerque, NM). There are unfortunately some benches and an earthen embankment in the vicinity, so care was taken to choose test locations that would avoid sound reflection artifacts from these modern objects. Conditions at the time of testing were 62.0°F and 14.3% relative humidity.
2) Box Canyon at the head of Holbert Trail in South Mountain Park. This site consists of steep rocky mountainsides forming an amphitheater-like enclosure. Conditions at the time of testing were 66.5°F and 22.5% relative humidity.

Techniques and Equipment

Standard architectural or room acoustic reverberation measurement methods (Lubman and Wetherill 1985) are readily adapted for rock art acoustical measurements. The essential objective of reverberation measurements is to determine the graphs of sound intensity versus time for the echoes or reverberation. A set of graphs are usually provided to cover a large portion of the frequency range of human hearing. Typically, the range of frequency (measured in "Hertz", or "Hz", which is the unit of frequency equal to cycles per second) considered is from 100 Hz to 10 kHz (10,000 Hz). For this purpose, graphs are made for a contiguous set of octave or 1/3 octave frequency bands (an "octave" represents a doubling of frequency) that cover the frequency range of interest.

Two distinct approaches to reverberation measurements are "transient" and "steady state". If done correctly, both methods yield the same results. Transient measurements are usually easier and are more common. With the transient method, a brief acoustic stimulus is employed to "insonify" a region. The stimulus must be both very brief and very intense. A handclap or the banging together of two rocks or sticks approximates an ideal transient acoustical stimulus. This may have been adequate in ancient times when ambient noises were lower and human hearing was better but may be unrealistically weak in modern times. Much more detailed and reproducible information can be obtained today with field-friendly sources such as a starter pistol. It was impractical to make rock art transient measurements using a large loudspeaker, amplifier, and an interrupted noise source, as they are often done in auditoria. Instead, transient measurements were made in this pilot study using a .22 caliber starter revolver, Precise International model 32425, and Precise crimped .22 (6 mm) ammunition. (Other methods will be attempted in future experiments, see Discussion section).

Brevity of the transient stimulus is required for two reasons. First, to prevent the stimulus from interfering with the echo, the stimulus must end before the echo begins. More precisely, the trailing edge of the stimulus signal must pass the microphone before the leading edge of the echo arrives. Second, the stimulus must be short enough to provide adequate energy over a broad range of frequencies: the spectrum of energy in a short stimulus peaks at a frequency of roughly 1/(stimulus length). In these studies, the transient stimulus time was indirectly determined to be about 0.6 millisecond, as inferred from the observation that spectral energy peaked at about 1.6 kHz. The pistol spectrum was broad enough to cover 20 kHz, which was more than adequate.

Intensity of the transient stimulus is required to provide reliable information. The stimulus must be energetic enough to overcome ambient noise. Since ambient noise varies with frequency, the stimulus spectrum should ideally be shaped to compensate for the ambient noise spectrum; this was not so in these studies with a starter pistol (see Results section).

To digitally record and analyze the sounds, a CEL Sound Analyzer, Model 593 was fitted with a 0.5" condenser microphone. A field calibrator, Model CEL 284/2 was employed to calibrate the system immediately before and after usage. The analyzer, microphone, and calibrator are also annually calibrated and certified by an independent laboratory. The sound analyzer was used in its 1/3 octave 'Fastore' mode. This permitted spectrum measurements to be made every 10 milliseconds (100 times each second) in each of thirty 1/3 octave bands from 20 Hz to 20 kHz. This provided 30x100 or 3000 measurements per second that were digitally analyzed and stored in the CEL 593 analyzer. The testing geometry was such that the decorated rock surfaces were approximately 75 feet from both the starter pistol and the microphone, which were separated by approximately 20 feet.

In addition to capturing and analyzing signals digitally, the sound analyzer's output jack permitted raw signal data to be stored externally for later analysis. For this purpose, data was stored on a Sony Digital Audio Tape recorder, Model TCD D7.

RESULTS

Below is a brief summary of results and lessons learned from this pilot experiment to test the feasibility of acoustical characterization of rock art sites using professional digital sound analyzer and recording equipment. All field equipment, including a calibrated condenser microphone, digital sound analyzer, digital recorder, and portable calibrator, worked well in this field study. The team returned with much more useful data than could be analyzed in the short time available. Only a tiny portion of the data is described here.

Characterization of ambient noise and acoustical stimulus

The spectra of the background and impulsive noises are shown in Figures 1A, B and C. These graphs and the others that follow are printed directly from the CEL 593 analyzer. Figure 1A shows a typical ambient noise spectrum at the Hedgepeth Hills site near Phoenix, AZ on 12/30/97, with bars showing noise levels measured in 1/3 octave bands.

Sound Pressure Level in "decibels (dB)" is shown on the Y-axis. Noise levels are measured in dB relative to a standard reference pressure used in acoustical work

(20uN/M^2). For example, the cursor shows that the 1/3 octave band centered at 100 Hz had a noise level of 52 decibels. A rule of thumb worth remembering is that each increase of 10 dB corresponds to a doubling of subjective "loudness". Thus, a noise level of 52 dB in the 100 Hz band would sound about four times as loud as a noise level of 32 dB in the same band.

Frequency is shown on the X-axis in this figure. The CEL analyzer can record up to 20 kHz. Humans with normal hearing can hear over a wide frequency range of about 20 Hz to 20 kHz; aboriginal people may have had even better high frequency hearing because of less exposure to intense noise. It is also true that very high frequency sounds do not carry far. This is because of the high sound "attenuation" of the atmosphere at high frequencies. This can be seen in Figure 1A: above about 1.6 kHz the ambient noise fell below 20 dB and was not measurable with these settings of the sound analyzer. The noise levels at high frequencies (about 0 dB above 3 kHz) were probably close to or below the threshold of human audibility at both sites tested. The most common natural sources of very high frequency sound are insects, and leaves and grass blowing in the wind.

It is clear from Figure 1A that the most intense ambient noise occurred at low frequencies. This was expected since low frequency ambient noise can travel over great distances (many tens of miles) and can pass through thin solid barriers with little attenuation. Low frequency ambient noise in the modern world tends to be dominated by transportation noise sources. Low frequency noise at the Deer Valley Rock Art Center was dominated by vehicular traffic noise. (Measurements were made with permission on a day when the Rock Art Center was normally closed to visitors, since footsteps and conversation render acoustic measurements impossible.) Low frequency noise at South Mountain park was dominated by aircraft noise. At both sites, low frequency noise was dominant and clearly audible. It seems likely that in the distant past low frequency noise was much lower than it is today. This may justify the use of more intense low frequency stimulus to overcome low frequency noise and permit measurement of low frequency echo components.

Figure 1B shows the spectrum of a pistol shot used to insonify the site (plot includes excitation plus the ambient noise). It was taken 50 milliseconds (1/20 second) after Figure 1A. From about 250 Hz to 20 kHz, the pistol shot has enough sound energy to overcome ambient noise. As will be shown below, the echoes measured were usually strong enough to overcome ambient noise above about 500 Hz, and sometimes as low as 160 Hz. This suggests that a different source would be needed to provide more low frequency sound energy.

Figure 1C shows the pistol shot-plus-noise spectrum for a repeat of the pistol shot just over one second later. The fact that noise levels are nearly the same shows that the pistol is a fairly repeatable source.

Characterization of the Acoustics at Rock Art Sites

Figure 2 is an "echogram", or time history plot, of sounds recorded within the Deer Valley rock art site at a location where petroglyphs are visible on the hillside boulders about half-way along the trail. This example shows a single starter pistol shot and the resulting reflections, with sound level in dB (on the Y-axis) versus time (on the X-axis), for the 1/3 octave band centered at 2 kHz. The entire event shown here spans a time interval of 1 second, with samples taken every 10 milliseconds. Notice the abrupt rise and fall in sound level at the moment the pistol shot is received. The slow decay in sound level is characteristic of reverberation, and there is apparently a discrete echo (at t = 13:32:56:700). In room acoustics, the reverberation is grossly characterized by the "reverberation time (RT60)" measured in seconds. An estimate of RT60 is made by fitting a straight line to the decay between the cursor positions as shown. RT60 is the measured or extrapolated time required for the reverberation to decay by 60 dB. The RT60 found here by a least squares straight line fit is 1.587 seconds at 2 kHz. This is nearly identical to the RT60 at the same frequency in New York's Avery Fisher Hall! This result typifies what was found at other rock art locations and at other frequencies.

Figures 3A, B and C show separate traces for the 500 Hz, 1 kHz, and 2 kHz bands (approximately the pitches of the musical notes B4, B5 and B6, respectively) of the time history for three successive pistol shots at the same Deer Valley location half-way along the trail. In Figure 3A at 500 Hz one can recognize the rapid rise and fall of each pistol shot and note the reverberant decay that seems to follow them, but this Figure shows inadequate signal strength in the 500 kHz band because the reverberant tail is quickly lost in the background noise. The problem at this low frequency is a poor signal-to-noise ratio ("SNR"). More signal energy is needed to overcome noise in this band of frequencies. Figure 3B at 1 kHz shows a much more satisfactory SNR. This is because, as shown in Figure 1, the signal strength is higher and the noise level is lower at 1 kHz than it is at 500 Hz. Another observable feature of Figure 3B is that all three decay traces are very similar. This similarity demonstrates that we are recording true characteristics of the site and not random variations. Figure 3C for the 2 kHz band shows an even higher SNR and good, but not perfect consistency in detail between traces (the third shot in Figure 3C was shown in detail as Figure 2). Actually, for various reasons, a certain amount of variability between traces is expected. For example, the pistol shots may not repeat exactly. There are well-developed methods for eliminating such variations. Trace averaging and "Schroeder integration" are two such methods. Neither was attempted here.

Figure 4 shows another succession of three pistol shots fired at a second Deer Valley location, where other petroglyphs are visible approximately three-quarters of the way along the trail from the Rock Art Center building. Comparing the traces of these replicate tests with each other again shows substantial consistency. Comparing these traces made at 1 kHz with the previous set of three traces (Figure 3B) made at the same frequency but at the first location, reveals differences and supports the notion that the reverberation at each site is unique (see Discussion).

Figure 5 at 1 kHz taken at a third Deer Valley location, facing the highest concentration of petroglyphs near the furthest point on the trail, is a further example of the unique acoustic characteristics of each location.

Figure 6 is an example echogram at 1 kHz of two successive shots at South Mountain Park, and represents the echoing and reverberation found in Box Canyon. Distinct echoes are heard with the ear, and these show at multiple times on the echogram as well. The RT60 of box canyon was measured to be 1.411 seconds at 2 kHz (data not shown). Thus rock art sites measured to date can be said to constitute acoustically live, or reverberant, spaces.

The illustrations in this paper represent a tiny fraction of the data collected, limited by space and analysis time. The data selected for presentation are key examples of the types of information gathered, and are representative of the data analyzed so far.

DISCUSSION

This study represents the first application of professional digital recording equipment and analysis techniques to the study of rock art. The results confirm earlier observations of echoes at these locations. The use of digital equipment was found to be an improvement over previous analog studies in the detail and amount of information garnered.

Reverberation and/or echoes were measured as well as heard at each decorated location tested at both rock art sites (see figures 2-7). The shape of the decays are unique characteristics of each site and even each location within the overall site. The details are visibly different for sets of traces made less than 200 feet apart. These differences may impart unique sound character to each rock art site.

A key learning from this first study was the unique challenges of rock art site testing. The remote and naturally primitive locations prevent the use of externally powered equipment, and dictate that all equipment must be easily portable. Ambient noises encountered at these sites included: talking and foot-steps of tourists to such a degree that some testing had to be rescheduled; transportation sounds that decreased the signal-to-noise ratio in the low frequency range; (and even rifle shots at Calderwood Butte, which is a popular spot for shooting practice, thus precluding inclusion of that site in this study despite the observation of a remarkable echo). Finding a portable excitation source that is sufficiently brief and intense enough to overcome ambient noise is a challenge to rock art acousticians.

The reason for the use of impulses in these studies may not be evident. On the most superficial level, one may surmise that aboriginal people may have heard echoes while hammering stone tools and other implements on rocks. Such actions create impulsive sounds and the echoes that result from them. But there are fundamental reasons for using impulses or their analytical equivalents for acoustic characterization. Although impulse measurements in these studies were so far used only to estimate crude echo and reverberation characteristics discussed below, it is worth noting that far more sophisticated uses can be made for these data. In principle, with knowledge of the impulse response it is possible to determine exactly how any sound would be modified by the acoustics of the site. For example, it is possible to hear how chant or singing would sound at a site, if we have measured the site's response to an impulse. This process is called "auralization", and is coming into more frequent use in contemporary architectural acoustics. The basic information needed for auralization is the impulse response of a site together with the music or other acoustic stimulus. The process of auralization involves mathematical convolution of the music signal with the site's impulse response. Although auralization was not attempted, sufficient information was collected so that this may be attempted in the future.

Even a cursory run through the data shows that the rock art locations tested have unique echo and reverberation characteristics. This was expected, since each site has a unique geometry and its elements have unique acoustical properties. Taken together, geometry and element acoustical properties characterize the site acoustics. Some of these unique characteristics must certainly have been perceptible to the rock artist. If the long reverberation decay times noted at these sites were measured in rooms, they would be characterized as rather reverberant, cathedral-like spaces, with liveliness comparable to modern concert halls purposefully engineered for good acoustics! Whether or not the artists were conscious of the unique sound at each location, it could have registered on their mind and influenced their choice of site or their artistic product. We have not attempted to determine the impact of unique acoustical features on the artist, but it seems reasonable to suppose there was such impact. It is known through a large number of legends that ancient cultures around the world attributed the phenomenon of echoing to supernatural spirits.

Possible Future Improvements In Techniques

The experience of this study suggested the potential for the application of various other techniques in the future, with an aim of developing a standardized procedure for the characterization of rock art acoustics as an integral part of rock art recording.

The method used for site excitation in this survey was conveniently simple, light, and portable. But it has serious shortcomings: not enough low frequency energy to overcome ambient noise; obtrusiveness (gunshots are loud and can be alarming); possibly unallowable since even starter pistols are restricted on certain sites. Other impulsive methods are possible (e.g., balloon bursts are now being investigated and appear promising). Outdoor ambient noise typically exhibits a spectrum that falls with frequency, and this is more easily compensated for using electronic sources having a "pink noise" spectrum, than using portable equipment.

Steady state methods, not used in this study, include the use of a pseudorandom signal such as the "MLSSA (Maximum Length Sequence Analyzer)". This has significant advantages. It uses a much less intense and intrusive test signal. Its chief disadvantage is the large amount of apparatus that must be carried to the site, including an amplifier, loudspeaker, and an electrical power source. Steady-state methods currently require considerable electronic support, are bulky, and therefore seem impractical at remote field locations at the present time.

It was not practical in the brief time available to determine quantitatively if the documented acoustics present at decorated locations were different (e.g., stronger intensity) than nearby non-decorated locations, as demonstrated by previous studies at other locations (Waller 1997). However, the effort of such quantitative studies are warranted by the results of the present study, since all three authors concluded that the sound of the echoes did seem to come from each place the artists had chosen to decorate.

This pilot study did not try to capture "binaural" (two-ear) effects, such as documentation of DOA, i.e., the perceived direction from which the reflected sound originates. The DOA is a potentially important issue in rock art acoustics, since it may relate to the artists' motivation for which surfaces to decorate. The acoustical methods described here do not measure the direction of echoes. The DOA can be represented as a "ray" or vector of direction. The direction of sound reflection from a large, smooth, hard, nonporous surface is predicted by "Snell's Law". Snell's law asserts that the angle of incidence of a ray of sound (or light), measured from the normal, is equal to the angle of reflection. For an observer standing in front of a wall, the angle from the normal is zero degrees. This explains why sound reflects directly back to an observer standing in front of a wall. The authors envision that binaural recordings made at acoustically sensitive sites may become a routine element in rock art site characterization. Having sound, as well as photographs of images, may provide important interpretive clues by capturing more fully the gestalt of the rock art experience. The benefits of bringing a multimedia rock art experience to the laboratory, lecture room, and museum seem self-evident. Pilot studies of this sort are now under way.

Conclusions

a). The experimental methods of architectural acoustics are applicable to the acoustical characterization of rock art sites. In particular, the use of digital recording techniques can rapidly collect large amounts of data for later analysis.

b). Impulse response measurement is the chief objective of acoustical characterization, in part because it permits auralization. This allows one to experience how any sound -- e.g., pecking or hammering of rocks, chanting, singing or other forms of music making -- would be modified by the site.

c). As expected, strong reverberation and/or echoes were found at each rock art location tested.

d). Each site appears to have a unique acoustic signature evident in the reverberant tail.

e). The starter pistol is a satisfactory source of insonifying energy only at the higher acoustic frequencies. A more suitable portable source of low frequency energy is needed to extend recordings down to frequencies as low as 100 Hz.

f). In the future, binaural recordings at rock art sites may add a useful dimension to rock art studies and presentations.

g). If the choice of location for rock art was acoustically motivated as hypothesized, a new dimension of conservation may be needed to protect the integrity of the sound characteristics of the site as well as the art itself.

In summary, professional digital acoustic analyses presented in this paper confirm earlier observations of sound reflection or back-scattering at rock art sites. The more detailed types of information gathered should prove useful in determining the relevance of acoustics to the study of rock art. The effect of sound-altering modifications on such studies, however small, underscores the need for the conservation of not only the art, but also the acoustics at rock art sites to enable future studies.

ACKNOWLEDGMENTS

The authors thank officer Vick Gonzales of the Deer Valley Rock Art Center for allowing access at a time the site is usually closed to visitors. The patience and understanding of Patrice, Jason and Julia Waller is gratefully appreciated.

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Attachments: Appendix (glossary) and Figure captions