Acoustic Heritage and Audio Creativity: the Creative Application of Sound in the Representation, Understanding and Experience of Past Environments

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Summary:

Acoustic Heritage is one aspect of archaeoacoustics, and refers more specifically to the quantifiable acoustic properties of buildings, sites and landscapes from our architectural and archaeological past, forming an important aspect of our intangible cultural heritage. Auralisation, the audio equivalent of 3D visualization, enables these acoustic properties, captured via the process of measurement and survey, or computer based modelling, to form the basis of an audio reconstruction and presentation of the studied space. This paper examines the application of auralisation and audio creativity as a means to explore our acoustic heritage, thereby diversifying and enhancing the toolset available to the digital heritage or humanities researcher. The Open Acoustic Impulse Response (OpenAIR) library is an online repository for acoustic impulse response and auralisation data, with a significant part having been gathered from a broad range of heritage sites. The methodology used to gather this acoustic data is discussed, together with the processes used in generating and calibrating a comparable computer model, and how the data generated might be analysed and presented. The creative use of this acoustic data is also considered, in the context of music production, mixed media artwork and audio for gaming. More specifically to digital heritage is how these data can be used to create new experiences of past environments, as information, interpretation, guide or artwork and ultimately help to articulate new research questions and explorations of our acoustic heritage.

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Key Words: Acoustics, acoustic heritage, archaeoacoustics, auralisation, sound, impulse response, soundscape, interpretation, performance, perception.

1. Acoustic Heritage

Archaeoacoustics refers to the study of sound in archaeological contexts (Scarre and Lawson, 2006), and is inherently multi-disciplinary, covering diverse fields such as archaeology, ethnomusicology, music archaeology, acoustics, engineering, modelling and simulation. *Acoustic Heritage* in the context of this article refers more specifically to the quantifiable acoustic properties of buildings, sites and landscapes from our architectural and archaeological past, both recent and more distant. As the tangible, physical aspects of such places are subject to change over time, then as a direct consequence so are their acoustic properties, determined as they are by the surrounding landscape or built environment. With such material change also comes a potential change of use, with the sounds originally heard within a given environment becoming replaced over time with contemporaneous equivalents. A better understanding of the sounds that would be present within a studied environment, and how this environment might then affect the sound propagating within it, enables us to consider what people inhabiting that space, at that time, might have heard. The consideration of our acoustic heritage therefore helps to build a more complete multi-sensory picture of our past, and the experience of being present within it. Although sound often takes second place to our more dominant visual sense, it plays a significant role in conveying complex information for rapid assimilation by a listener. Speech and music are obvious examples

of this, but the creative use of sound can be used to create highly evocative, engaging and immersive audio or multimedia experiences, and none more so than in considering past environments. The study and preservation of our acoustic heritage therefore becomes as important for understanding the past as any other property, be it material or visual.

Acoustic heritage translates between the concepts of both tangible and intangible heritage. Fundamentally it is founded in physical, tangible aspects of our past environments – the wood, stone, brick and other materials we have used to construct our society around us – that, give rise to the intangible: the acoustics of, and sounds associated with, these spaces, and our experiences of them. The sounds we make are transformed by the materiality of our environment and so, therefore, is our lived experience. This relationship between the tangible and intangible in terms of acoustic heritage has been explored in other contexts, for instance in the case of popular music production and 'place-making' (Darvill, 2014). However, the wider acceptance of sound as *intangible cultural heritage*, as defined in (UNESCO, 2011) is debated, in part due to this particular definition having associations with legislative or political interests (Kytö et al., 2012). Kytö et al., go on to define acoustic heritage in a European context as being, "any sounds that form a testimony of a sonic situation" (Kytö et al., 2012, p.68), and certainly the definition of acoustic heritage adopted in this paper, that is, the quantifiable acoustic properties of buildings, sites and landscapes from our architectural and archaeological past, falls within the scope of this more broadly defined model. Other authors see no difficulty in assuming this more specific definition of acoustic heritage as being a clear example of intangible cultural heritage (Brezina, 2013), and how methods drawn from disciplines such as acoustics, engineering, music production, modelling and simulation can be applied in acoustic heritage research.

Early work in the archaeology and heritage of acoustics explored the low frequency resonances of megalithic prehistoric monuments in the UK through direct excitation (using a loudspeaker) and sound level measurement and analysis, together with more qualitative methods (Watson and Keating, 1999). This methodology has since been updated and applied in recent studies of an ancient hypogeum in Malta (Debertolisa et al., 2015). However, the more complete acoustic capture of a site, through a process of measurement, modelling or some combination of both approaches is still relatively novel in wider archaeological studies, despite having been applied in acoustic and creative audio fields for some time e.g. (Weitze et al., 2002a), (Farina and Ayalon, 2003), (Murphy, 2005), (Murphy, 2006). The application of such acoustic methodologies in an archaeological context is discussed in (Brezina, 2013) and acoustic modelling and simulation have been used in a number of studies including the ancient theatre of Epidaurus in Greece (Lokki, et al, 2013), the Hagia Sophia in Turkey (Weitze et al., 2002b) and the abbey church of St Mary's, York, UK (Oxnard and Murphy, 2012). Sound propagation modelling was used to produce a sound level map of the landscape surrounding Silbury Hill, UK (May, 2014), to better understand how this monument might have affected the perception of speech and other sounds heard in the area around it. Acoustic measurement has been used to study the contemporary acoustic properties of an open-air medieval performance space in York, UK (Lopez et al., 2013). These acoustic measurements were then used to inform a series of acoustic models recreating the sixteenth-century space (Lopez, 2015), to better understand what audiences of the time would have heard of these performances. This use of acoustic measurement to inform the acoustic modelling process has also been applied in a number of other studies including an exploration of the acoustic heritage of mosques and Byzantine churches (Weitze et al., 2002a), and the sounds associated with the landscape and environment around Stonehenge (Fazenda and Drumm, 2013). The goal in many of these studies, aside from deriving acoustic measures that help to characterize and quantify an environment in objective terms, is to produce an *auralisation* – an acoustic reconstruction of what the environment would have sounded like at a given point in its history, and hence a better understanding of the subjective sonic experience of being present in that place at a given time. Informed by such previous studies, this paper therefore sets out to examine the context of, and establish the methodologies appropriate to, the application of auralisation and audio creativity as a means to explore our acoustic heritage.

1.1 The Acoustic Impulse Response

The acoustic measurement of an existing building or landscape enables the capture of characteristic audio *impulse response* data that can be used to help preserve a site's intangible acoustic heritage and allow further analysis of its sonic features. Where acoustic measurement is not possible, computer modelling allows us to imagine, build and interact with these sites in the digital domain. This may involve the adaptation of an existing site to investigate particular features, or the reconstruction of a building that no longer exists, or only exists in part.

[figure1.tif]

Figure 1: The echogram profile of a typical impulse response from an enclosed space, demonstrating how a short, impulsive sound – like a handclap, balloon pop or gun-shot – at the source position arrives at the measurement position in three stages: (a) the direct sound arrives via the straight line path between sound source and measurement position, arriving a short time after the sound source has stopped; (b) the early reflections arrive via the next longest paths from source to measurement position, involving one or more reflections from the main surrounding walls, where some additional energy will be lost due to sound absorption; (c) the reverberation or exponential reverberant decay, where it is no longer possible to detect distinct reflections due to the density of arrival of many reflections via many paths, involving reflections from multiple walls.

1.2 Auralisation

Auralisation enables these acoustic impulse response measurements or computer models to form the basis of an audio reconstruction and presentation, so that we might place and manipulate any sound within a studied site or landscape, and listen again to the echoes and resonances that are produced. It therefore becomes possible to piece together the collapsed stones of medieval buildings and listen again to the echoing words of the people who inhabited them (Oxnard and Murphy, 2012). Stonehenge can be reconstructed, ignoring modern elements such as noisy roads and aircraft, and place the listener in the very centre of the structure, to experience the sound of a ritual as the sun rises on the solstice (Fazenda and Drumm, 2013). Experiments with building materials and construction techniques enable exploration of how actors would be heard across a Greek or Roman amphitheatre (Rindel, 2011). The medieval streets of York can be reconstructed to understand how well audience members would have perceived the dramatic performances of the York Mystery Plays (Lopez, 2015). Auralisation also enables the acoustic preservation of aspects of our intangible cultural heritage (Brezina, 2013). The often cited example being that of the Gran Teatro La Fenice in Venice, which was subject to an extensive fire on the night of 29 January 1996. Two months prior to the fire acousticians Lamberto Tronchin and Angelo Farina made several acoustic measurements within the building, and this key interaction helped to preserve the sound of a much loved opera house as well as help with its subsequent restoration (Tronchin and Farina, 1997).

Auralisation can therefore be considered as the aural equivalent of 3D computer visualization. Although auralisation has long been used in the field of architectural acoustics (e.g. Kleiner et al., 1993), in digital heritage, it is beginning to take its place alongside the more established discipline of visualization, for interpretation, understanding and research. Developing these ideas further, auralisation can also be used as a means to facilitate modern interventions with heritage sites, and so allow sound designers and artists to better use the broadband information processing capacity of our hearing system to present new and novel soundscapes to an audience, be this as information, interpretation, guide or artwork.

However, questions of accuracy and authenticity should always be considered in tandem with such acoustic reconstruction and manipulation. Objective analysis of acoustic parameters can only reveal so much about how a space, or event within it, might have actually sounded. Subjective, perceptual testing goes some way further, although the context of both the site and the sounds being auditioned are not commonly considered in such tests. Perhaps more important in digital heritage – although more difficult to quantify – is the quality of experience that arises as a consequence of any auralisation. What can we learn about a site and the people who used it from how we perceive and interact with a virtual representation?

1.3 The OpenAIR Library

This paper will go on to consider the use of auralisation and audio creativity in the context of digital heritage, documenting the process of acoustic measurement and modelling that is involved, as well as how the results can be applied in a variety of contexts. In particular this article provides a narrative accompaniment to the ongoing Open Acoustic Impulse Response (OpenAIR) library project (Shelley and Murphy, 2010), (Shelley and Murphy, 2011) – an online repository for acoustic impulse response data, a large part of which are collected from a broad range of heritage sites. The OpenAIR library[1] enables the interested enthusiast or acoustic expert to explore, interrogate, analyse and audition the data that has been collected. The results can be downloaded in various audio formats for further individual use under a Creative Commons license, and third-party uploads are also possible, which has enabled this project to be expanded worldwide. The reader is encouraged to explore the OpenAIR website for themselves, although key illustrative examples are presented here directly as part of this paper.

2. Virtual Acoustics and Auralisation

We have come to accept and appreciate visualization as an art form via the modern use of computer graphics in film, television and video games. Computer visualizations are easy to comprehend and appreciate, and they can impart such a sense of quality that we accept them as some form of reality, be they based on actual real-world scenes or an imaginary subject or landscape. We are visual beings and computer rendered visualizations, whether static or dynamic, allow us to pause and appreciate, for instance, the beauty of detail, colour, or depth of field of the rendered scene. Recreating the auditory equivalent using auralisation, however, is in many ways a much more complex process - it is a constantly changing, ephemeral experience with few fixed points of reference (unlike a visual landscape), and our perception and understanding of it can depend on many different aspects - our own personal sound experiences; the choices made by the designers in presenting the audio material to the listener; whether this is for personal listening (headphones) or shared experience over multiple loudspeakers (as in the cinema) - but the results can leave an impression or memory with us after images have long since faded. Our ears and brain are finely tuned interpreters of many competing streams of complex auditory information, and are sensitive to a broad range of acoustic sensations, both in terms of frequency (from bass to treble) and dynamic range (from silence to the threshold of pain).

One formal definition of Auralisation is as follows:

"...the process of rendering audible by physical or mathematical modelling, the sound field of a source in space, in such a way as to simulate the binaural listening experience at a given position in the modelled space" (Vorländer, 2008).

The starting point is a *model* of a particular environment. The classic example, from where much of this research has originated being a concert hall. Into this environment, we place a sound *source* (for instance, an opera singer, in the example of a concert hall) at a particular location (on the stage) and a *listener* (situated in what might be considered as the best seat in the house). We then wish to recreate for this listener the *binaural listening experience* of the opera singer on the stage of the modelled concert hall, as heard from their seat. More rigorously we wish to recreate the acoustic pressure sensations at each of the listener's eardrums (hence *binaurally*). This requires acoustic knowledge about the sound source - the properties of the human voice when singing opera; the directions in which the sound travels, and how these properties vary over time or with audio frequency. Knowledge of how the sound waves, so created, propagate through the concert hall is necessary, including: the distance travelled before arriving at the listener's ears, changes imparted through interactions with a wall or an object within the room, and the effect of air as the medium on the sound waves passing through it. It is also important to have information about the listener's head and ears - the size and shape of the outer ears (pinnae); whether the listener moves their head or remains static. Finally, this modelled sound needs be presented to the listener

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[1] http://www.openairlib.net/

- over headphones, or over two (stereo), or more (surround-sound) loudspeakers; if loudspeakers are to be used, will the listener be positioned in the middle of them – at the so called *sweet-spot* – or in a non-optimal seating position as part of a wider audience (as in cinema presentation). Auralisation separates the experience of listening to a sound within a given environment into the constituent acoustic elements, from sound source to listener's ear, and how this same effect can then be reproduced over an audio system. As a result this whole listening process can be better understood, and with understanding comes the ability to control, reshape and re-imagine the listening experience.

2.1 Modelling and Measurement

Acoustic modelling is generally used in auralisation to predict sound propagation behaviour in a space that does not as yet exist, and so is a key design process in the development of new performing arts venues, where acoustic quality is critical (Schroeder, 1973). It is also used to predict the acoustic consequences for refurbishments planned in existing venues. Traditionally, the model might in fact be a reduced scale construction of the actual building, complete with miniature loudspeakers (for sound sources) and microphones (for the listener's ears), with the audio signals scaled up in frequency accordingly to compensate for the change in physical dimensions (Polack et al, 1993). Such techniques are now rarely used due to the high level of skill needed in the construction, not to mention the time required to build them, the high costs involved and the limitations of the miniature audio systems used.

Computer based acoustic modeling (Välimäki et al., 2012), (Savioja and Svensson, 2015), is therefore much more established, based on 3D computer aided design techniques, and makes it possible to use a computer generated *visualization* and from this derive an *auralisation*. Despite the flexibility that this implies (it is much easier to edit, change and experiment with the design of a computer based environment than with a comparable scale model, or even the real thing), the accuracy of the result is still only as good as the mathematical techniques that are used to describe how sound behaves within this virtual 3D space. As yet there is no perfect solution for this problem. Most existing commercial software makes use of one or more *geometric acoustic modelling* techniques (Savioja and Svensson, 2015). Here, sound is assumed to travel in straight lines, similar to a ray-of-light, and sound paths are calculated from source to listener based on how these predicted paths interact with the surrounding geometry of the environment and reflect from walls and objects. The result is a close approximation to the impulse response of the modelled environment, for a given set of conditions, although results at low frequencies are often less accurate, as geometric acoustic methods are less able to model the wave-like behaviour of sound at these frequencies. This problem is an area of active research and an alternative approach is to use a numerical method to solve the underlying equations of wave motion (van Mourik and Murphy, 2014). Although more accurate, such methods are too expensive computationally to offer a complete solution, taking hours, days, or weeks to arrive at the final result, and hence hybrid methods, taking advantage of both approaches, are also an area of current research (Southern et al, 2013).

[figure2.gif - GIF Animation of Geometric Acoustic Method – St Mary's Abbey]

Figure 2: This animation depicts geometric acoustic sound propagation. The model, shown in plan view is a reconstruction of St Mary's Abbey Church, York (see Section 5). An impulsive sound source is introduced into the space, and the resulting sound propagation paths are visualized as a circular spread of 'billiard balls' travelling out into the modelled volume and undergoing reflection when they interact with bounding surfaces and objects within the space.

Despite there being limitations to the methods used in acoustic modeling, it is still possible to get very close to an optimal result, and certainly to a point that the resulting auralisations are considered to be perceptually plausible, or 'good enough'.

Acoustic measurement for auralisation is the real-world equivalent of acoustic modelling. As with computer-based modelling, the goal is to obtain a set of acoustic impulse responses from the measured space that can be used for further analysis, to better understand how the space has an impact on sounds heard within it, or for auralisation. Although it is possible to arrive at an approximation of the acoustic impulse response by using a balloon pop or starter pistol as the

sound source excitation, recorded at the required listener position, it is much more common to use an analytical signal played back through a loudspeaker. The method presented in (Farina and Ayalon, 2003) based on an exponential sine wave sweep through all frequencies of interest (typically 22Hz to 22kHz to cover the complete audio spectrum) is now widely used, with additional post-measurement processing applied to inverse filter the sweep signal to arrive at the required impulse response.

[figure3.tif]

Figure 3: Frequency-domain spectrogram of the exponential sine sweep sound source excitation signal, from 22Hz to 22kHz, used as the analytical signal played back through a loudspeaker. The signal effectively sweeps through the audio spectrum so that the acoustic response of the measured space is captured for each frequency.

[figure4.tif]

Figure 4: Frequency-domain spectrogram of the measured exponential sine sweep sound source excitation signal as captured at the receiver microphone. Note the blurring of the most prominent sweep when compared with Figure 3, demonstrating the decay of sound energy at each frequency due to the acoustic response of the space. The additional, fainter sweeps, are due to distortion introduced by the measurement transducers, and other evident signal components are due to additional noise present during the measurement process.

[figure5.tif]

Figure 5: The final time-domain impulse response waveform arrived through post-measurement processing to inverse filter and window the measured sweep signal shown in Figure 4. The additional non-ideal signal components introduced during measurement can be very effectively minimized during this processing, resulting in a very clean and high quality result, suitable for auralisation and further analysis.

The loudspeaker used as the sound source is of some importance for an optimal result. Acoustic standards recommend an omnidirectional loudspeaker so that the measured space is excited equally in all directions (ISO3382-1, 2009), although this is more usually applied for acoustic analysis rather than auralisation. Omnidirectional loudspeakers are often not ideal for auralisation – they have a non-flat frequency response that will colour the excitation signal and therefore also the recorded measurement, and at wavelengths (and hence higher frequencies) comparable or shorter than the loudspeaker driver diameter, actually become highly directional. Furthermore, auralisation is designed to simulate a specific sound played back in the measured space and the most commonly used acoustic signals (e.g. speech, musical instruments) have a particular directional characteristic. Hence an omnidirectional loudspeaker over-illuminates the environment with acoustic energy in a way that real acoustic sound sources rarely do. For this reason, high quality recording studio monitor loudspeakers are often used (Farina and Ayalon, 2003), (Murphy, 2005), (Murphy, 2006), (Lopez et al., 2013) – they have a typically flat and extended frequency response with good coverage of both low bass and high treble ends, and a directional characteristic that is generally uniform with frequency. If a more omnidirectional excitation is required, it is possible to orientate the loudspeaker to different directions and sum across the results obtained (Shelley et al, 2013). Some *equalisation* of the recorded measurements might then be needed to account for too much bass energy in the resultant sum as such loudspeakers tend to be more omnidirectional in this frequency range in any case.

[figure6.jpg]

Figure 6: Loudspeakers used as the sound source for OpenAIR acoustic measurement: the Genelec S30D studio monitor, used for best results but limited to indoor spaces only, in this case St. Patrick's Church, Patrington, UK.

[figure7.jpg]

Figure 7: Loudspeakers used as the sound source for OpenAIR acoustic measurement: the Genelec 8130A is a good compromise when portability is required, as shown here when measuring Troller's Gill limestone gorge in the Yorkshire Dales, UK.

A combination of microphones at the listener position to record the signal propagating through the space from the source loudspeaker makes it possible to capture a large amount of impulse response data in one pass. Getting access to a site for study is often difficult, and usually only a small window of opportunity is available away from normal activities, when both interior and exterior environments are quiet enough to enable high quality acoustic measurements to be made. Hence it is important to gather as much data as possible in a short time frame. This approach was pioneered in (Farina and Ayalon, 2003), where a stereo microphone pair, a binaural dummy head microphone and an Ambisonic B-format Soundfield microphone[2] are used together in combination with a rotating turntable to automate the measurement process. This microphone array takes 36 sets of measurements over eight-channels at 10-degree intervals. An alternative version was used in (Murphy, 2005), (Murphy, 2006), and forms the basis of most of the measurements available on OpenAIR. In this configuration a Soundfield microphone is positioned on a boom arm, 1m from the centre axis of the automated rotating turntable. A single Neumann KM140 cardioid microphone is situated with the capsule end 10.4 cm from the centre axis, essentially one half of an ORTF stereo microphone pair spaced 17cm apart at an angle of 110-degrees. Both microphones are set at a height of 1.5m and a rotation increment of 5-degrees is used. This simplifies the system used in (Farina and Ayalon, 2003), but still enables the 72 sets of five-channel impulse response information to be combined for a wide variety of surround-sound auralisation or acoustic analysis options.

As the OpenAIR database expanded to include outdoor environments, the measurement system used was simplified further for the sake of portability, and became based around a single Soundfield microphone. The Soundfield microphone used across all of these methods consists of a four-channel coincident array of microphone capsules that spatially samples (or records) the acoustic field at a given point. It is compact, simple and easy to use, does not require complex calibration, and gives flexible rendering options for decoding the impulse response measurements for many types of speaker configuration, including binaural sound via a further post-processing and signal transformation stage. Soundfield microphone recordings/measurements also form the basis of parametric spatial audio rendering techniques (Merimaa and Pulkki, 2005), (Berge and Barrett, 2010) that have the potential to give better spatial accuracy for a wider group of listeners within a loudspeaker array, without having to resort to microphones based on more complex spatial arrangements and higher channel counts.

[figure8.jpg]

Figure 8: Microphones used at listener position for OpenAIR acoustic measurement: Soundfield SPS422B and Neumann KM140 mounted on automated turntable, with the centre axis of the turntable located at the listener position, shown in the R1 Nuclear Reactor Hall, Stockholm, Sweden.

[figure9.jpg]

Figure 9: Microphones used at listener position for OpenAIR acoustic measurement: close-up of the Soundfield ST450 used for single point measurements when portability or speed of measurements is a factor, here shown in the circle of the York Theatre Royal auditorium.

2.2 Analysis and Reverberation Time

The fundamental quantity used to characterise, define or gain information about the acoustic qualities of a particular space that can be obtained from an impulse response is *reverberation time*. Reverberation time (or RT60) is formally defined as the time it takes (in seconds) for a steady state signal to attenuate by 60 decibels once the sound source has stopped (Sabine, 1922). Perceptually, RT60 is the formal quantity we associate with a space we might consider as being *echoey* or *spacious*. Such a space might have an RT60 value of 2 seconds or more. A space considered as being *dry* or *dead* sounding might have an RT60 value of less than 0.5 second. An *anechoic* space is specially designed to absorb all sound and so would ideally have an RT60 of zero seconds. Reverberation time varies with frequency, and is typically quoted in octave bands (the audio spectrum divided into 10 octaves between 20Hz and 20kHz, with an octave defined as a

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[2] http://www.tslproducts.com/soundfield-type/soundfield-microphones/

doubling in frequency). The graph below shows RT60 values, quoted for each octave band, for a range of spaces found on OpenAIR:

[figure10.tif]

Figure 10: Reverberation time (RT60) measured in seconds across octave bands from 125Hz to 8000Hz, for four varied acoustic spaces available on OpenAIR: Hamilton Mausoleum, Koli National Park (Winter), York Minster, and the R1 Nuclear Reactor Hall.

Other acoustic parameters can also be derived from an impulse response measurement, and are commonly used to provide additional detail in the acoustic characterisation of a particular space. These parameters form an important part of the modern architectural design process and have been documented in the relevant international standard (ISO3382-1, 2009). They have also been adopted in studies relating to acoustic heritage as they are able to give insight into, for instance, the intelligibility of speech or music in a particular space. However, it is also possible to interrogate this digital data in other meaningful ways. Analysing the frequency content of such time varying impulse response measurements helps to reveal how low frequency sound behaves, and whether there are specific resonances that might act to influence or colour how sound is perceived. If spatial impulse response measurements are available, as obtained from a Soundfield microphone, it is also possible to conduct a reflection analysis to detect from which directions, and hence from which walls, specific sound reflections come from. Again, such information can help to reveal how humans might interact with such sonic features or the acoustic consequences of how a space is changed architecturally over its lifetime. The following example shows a frequency and reflection analysis for the main chamber in Maes Howe passage tomb (Murphy, 2005), a small but highly reflective and resonant space.

[figure11.tif]

Figure 11: A series of analyses of one impulse response measured in Maes Howe passage tomb, Orkney, UK: time domain waveform plot of the actual impulse response.

[figure12.tif]

Figure 12: A series of analyses of one impulse response measured in Maes Howe passage tomb, Orkney, UK: frequency response obtained from time domain waveform plot in Figure 11 – note the large individual peaks below about 300Hz indicating a highly resonant space that would emphasize those particular frequencies of any sound heard within it.

[figure13.tif]

Figure 13: A series of analyses of one impulse response measured in Maes Howe passage tomb, Orkney, UK: reverberation time (RT60) obtained from time domain waveform plot in Figure 11, varying with octave band between 250Hz and 800Hz, noting that the overall decay of sound is very short.

[figure14.tif]

Figure 14: A series of analyses of one impulse response measured in Maes Howe passage tomb, Orkney, UK: spectrogram obtained from time domain waveform plot in Figure 11 showing how the frequency content of the impulse response changes over time, with a quiver plot reflection analysis overlaid indicating from which direction parts of the measured impulse response are arriving at the microphone – the direct sound and first reflection are particularly evident in this example.

2.3 Auralisation, Rendering and Convolution Reverberation

Once an impulse response has been obtained from either the measurement or modelling process, it can be used to process any audio signal or sound recording. Ideally this source signal should be completely anechoic – that is, having no reflections or acoustic environment information imprinted on it already – and this is what is generally known as *auralisation*, as articulated in the definition quoted from (Vorländer, 2008) above. This auralisation process results in the original anechoic source sound being heard as if it were played back in the measured or modelled space, at the position of the source from the perspective of the listener. This auralisation may then be rendered in any number of ways, from basic mono, through to full binaural reproduction over headphones, or surround-sound listening for a larger audience over a multi-loudspeaker array. The audio rendering

of an acoustic space with impulse responses obtained from either a measurement or a model is also known as *convolution reverberation* (Välimäki et al., 2012), as the audio signal processing theory used to facilitate this is known as convolution. There is little actual difference in terminology in this respect, although auralisation generally refers to the recreation of a particular sound event in a particular environment, whereas convolution reverberation is a technique more generally applied in music production or computer based composition. In the latter case, an aesthetically pleasing creative result is usually the goal, rather than a more exact virtual model of an actual physical process.

3. Case Study: St Margaret's Church, York, UK

St Margaret's Church, York, UK dates from the 12th century, of which the south porch is the only surviving aspect. The nave is 14th century and the tower was rebuilt between 1684 and 1685. Extensive restoration took place in the mid-19th century with the church finally declared redundant in 1974[3]. In 2000 the church reopened as the National Centre for Early Music and it is now in regular use as a venue and performance space. As part of the redevelopment acoustic treatment was added - reversible acoustic panels are arranged around the main walls of the venue, and drapes hang in the ceiling space above the lighting frame. The acoustic characteristics of the venue can therefore be changed easily depending on its desired use and hence RT60 values vary from around 2.0s (for large choral ensembles) down to 1.0s (for maximising speech intelligibility) depending on how the panels and drapes are arranged.

[figure15.jpg]

Figure 15: Reversible acoustic panels on the north wall of St Margaret's Church, York, open, so that they are most absorbing of incident sound energy.

[figure16.jpg]

Figure 16: Reversible acoustic panels on the north wall of St Margaret's Church, York, closed, so that they are most reflecting of incident sound energy. Note that at the top of the image, the roof lighting tracks can be seen, and it is above these that the variable closure drapes are situated.

For this case study three combinations of panels and drapes were used. Impulse responses were gathered using the exponential sine sweep method as source excitation, with a frequency range of 22Hz to 22kHz, and a sweep duration of 15s. A Genelec S30D loudspeaker was used as the sound source (S) placed half-way along the length of the south wall, facing towards the north wall. A grid of 26 receiver positions was plotted and at each a 4-channel measurement was made using a Soundfield SPS422B microphone.

3.1 Modelling and Calibration

A computer model of St Margaret's Church was also developed, using two leading commercial applications, CATT Acoustic[4] and ODEON[5], initially based on the architectural plans created during the most recent refurbishment of the space (Foteinou and Murphy, 2011). These were adapted further based on physical measurements taken during the acoustic surveying process, and taking account of additional objects and furniture that had not been included in the original architectural plans. There are no standards providing recommendations about the level of the geometric detail that should be considered in such an acoustic model. However, apart from being impossible to simulate every object and structure within a space, an extremely detailed model causes a significant increase in the number of the reflections that have to be considered by the geometric acoustic algorithm used in these applications, leading to a potential loss of accuracy in

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[3] http://www.ncem.co.uk/?idno=245
[4] http://www.catt.se/
[5] http://www.odeon.dk/

the results, especially for low frequencies. Hence an appropriate 3D acoustic model was defined for both applications to the same level of detail, as shown below.

[Figure17.tif]

Figure 17: Computer model representations of St Margaret's Church: CATT Acoustic model, looking towards the east wall. The sound source is represented by the red sphere, with the grid of receiver positions represented by the arrangement of blue spheres.

[Figure18.tif]

Figure 18: Computer model representations of St Margaret's Church: ODEON model, looking towards the west wall and the tower. Again, the sound source is represented by the red sphere, with the grid of receiver positions represented by the arrangement of blue spheres.

Once the 3D model was completed the acoustic characteristics of the surfaces within the model were defined as these play a crucial role in the accuracy of the acoustic results obtained from the simulated space. Defining these characteristics is often a challenge for acousticians with the main limitation being that the user has to rely on the material data provided in existing libraries that list frequency dependent absorption and scattering coefficients that determine how sound interacts with a given surface. It is not likely that an exact match will be found for the specific materials required for a given project, and even then, as construction techniques vary, there may be some variance.

In this case study an extensive calibration process was performed with a view to arriving at an accurate, optimal set of surface definitions. Although other methodologies have been proposed in the literature (Postma et al, 2015) the approach taken here can be summarized as follows:

(1) First choice materials were drawn from absorption coefficient data from existing software libraries and based on literature review of prior work in the acoustic modelling of similar spaces.
(2) Omnidirectional W-channel impulse responses from the Soundfield microphone measurements were used as a reference, comparing early reflection energy with that observed from the corresponding modelled positions (noting that both CATT Acoustic and ODEON are capable of giving similar Ambisonic B-format Soundfield-type measurement results). The absorption coefficients of the main walls were adjusted accordingly.
(3) This process was carried out for each measurement position for a single configuration of panels/drapes. Note that it is more usual practice to optimise these values based on RT60 values averaged across frequency band and position, with the consequence being that a lot of detail is often lost as part of this averaging process.
(4) Scattering coefficients were based on an estimation of the roughness and dimensions of the surfaces, again compared and confirmed based on prior work.
(5) The same material absorption and scattering coefficients were then used for the second and third configurations of panels and drapes.

Finally, the frequency and directional dependent properties of the Genelec S30D sound source were also modelled in both CATT and ODEON acoustic software applications to ensure a close approximation to the original measurement conditions. Figure 19 presents RT60 measurements across octave bands for the 17th microphone receiver position, based on the first configuration of panels/drapes, as derived from impulse responses obtained from acoustic measurements and the corresponding ODEON and CATT Acoustic models, post-calibration. The ODEON model gives an excellent match to the measurement case, with the CATT Acoustic example being sufficiently close. A set of auralisations generated from these examples follows, using a solo female soprano, recorded in anechoic conditions, as the sound source.

[figure19.tif]

Figure 19: Post calibration reverberation time (RT60), measured in seconds across octave bands from 125Hz to 8000Hz, for St Margaret's Church, York, UK. These values are for the 17th receiver position, with the first configuration of panels/drapes, as derived from impulse responses obtained from acoustic measurements (circles), the corresponding ODEON model (crosses), and CATT Acoustic model (squares).

[soundexample1.wav]

Sound Example 1: Female soprano, recorded in University of York, anechoic chamber.

[soundexample2.wav]

Sound Example 2: Impulse response obtained from acoustic measurements of St Margaret's Church, York, UK (17th receiver position, first configuration of panels/drapes).

[soundexample3.wav]

Sound Example 3: Post calibration impulse response obtained from the ODEON acoustic model of St Margaret's Church, York, UK (17th receiver position, first configuration of panels/drapes).

[soundexample4.wav]

Sound Example 4: Post calibration impulse response obtained from the CATT Acoustic model of St Margaret's Church, York, UK (17th receiver position, first configuration of panels/drapes).

[soundexample5.wav]

Sound Example 5: Auralisation obtained from the convolution of Sound Example 1 (Anechoic soprano) and Sound Example 2 (acoustic measurements of St Margaret's Church, York, UK, 17th receiver position, first configuration of panels/drapes).

[soundexample6.wav]

Sound Example 6: Auralisation obtained from the convolution of Sound Example 1 (Anechoic soprano) and Sound Example 3 (ODEON acoustic model of St Margaret's Church, York, UK, 17th receiver position, first configuration of panels/drapes).

[soundexample7.wav]

Sound Example 7: Auralisation obtained from the convolution of Sound Example 1 (Anechoic soprano) and Sound Example 4 (CATT Acoustic model of St Margaret's Church, York, UK, 17th receiver position, first configuration of panels/drapes).

3.2 Results, Analysis and Data Visualization

This measurement and modelling process results in a multi-acoustic parameter dataset that varies with frequency, model/measurement scenario and spatial position, making more comparative analysis and interpretation difficult to achieve. Data visualization is often used to help in these cases, and we have developed a novel method based on *acoustic floor maps* (Foteinou and Murphy, 2014) to help represent this multivariate dataset that combines position and frequency dependence for each acoustic parameter in a single plot. These acoustic floor maps use a radar chart, as shown in Figure 20, centred at each of the 26 measurement positions, with acoustic data presented clockwise across 6 octave bands, 125Hz, 250H, 500Hz, 1kHz, 2kHz and 4kHz.

[figure20.tif]

Figure 20: Radar charts represent the values of a given acoustic parameter at each individual measured position clockwise across the 6 octave bands, 125Hz, 250H, 500Hz, 1kHz, 2kHz and 4kHz.

[figure21.tif]

Figure 21: Acoustic floor map of T30 values obtained across the grid of 26 receiver positions, varying with source orientation 0°, 40° and 70°.

[figure22.tif]

Figure 22: Acoustic floor map of EDT values obtained across the grid of 26 receiver positions, varying with source orientation 0°, 40° and 70°.

[figure23.tif]

Figure 23: Acoustic floor map of C80 values obtained across the grid of 26 receiver positions, varying with source orientation 0°, 40° and 70°.

Three acoustic parameters are presented in Figures 21, 22 and 23, respectively T30, EDT and C80. T30 is equivalent to the generic term RT60, but derived more specifically from an impulse response measurement according to (ISO3382-1, 2009). EDT is an equivalent measure of RT60, but takes into account the early sound of the impulse response, rather than just the reverberant decay, and so gives an indication as to what impact early reflections have on the overall acoustics of the space, in particular in relation to the perception of the reverberant decay. C80 is also referred to as clarity and is a measure of the overall acoustic energy arriving at the listener before and after 80ms. Positive measures of C80 indicate more energy in the early sound, rather than the late, with the implication that the sound source will be perceived more clearly. Negative values of C80 indicate the converse, with the late reverberation dominating, meaning that, for instance, speech might be difficult to understand due to the reverberation in the space causing words to blend together, noting also that this might be favourable for certain forms of music.

The results of each acoustic parameter are demonstrated on the corresponding acoustic floor map, representing the values across six octave bands for each individual measured position. It can be observed that T30 values are not affected by the orientation of the sound source. EDT values have minimal changes, especially at those positions where physical characteristics of the space (such as walls or columns) combined with the effects of the source orientation influence the energy of the early reflections. However, early reflections appear much stronger than the direct sound when the source is oriented from 0°, 40° and 70°resulting in wider variations in C80.

4. OpenAIR and Acoustic Creativity

This process of survey and measurement, modelling, analysis and auralisation helps to provide an additional insight as to the properties and experience of being within a given space or environment, and can also be used to measure and map related changes over a period of time. As this research has developed, a significant body of acoustic data has been generated resulting in the OpenAIR library. This resource has therefore become a record of the acoustics of sites of historic interest around the UK and since expanded to cover additional similar sites around the world, together with outdoor environments and model based auralisations. As a consequence of the breadth of these data, OpenAIR has also become a key resource for electronic musicians, sound designers, software developers and computer game authoring houses. When this work was started in 2004 it was informed by the audio technology and computer music resources of the time. In 2004 the technology available to realise and render the acoustic measurements that were to be obtained from the spaces studied was not so common. Real-time multi-channel auralisation required high-performance, high cost hardware, often confined to research labs, industry and high-end music studios. Software versions of the same, in the form of audio plugins for common desktop computer digital audio workstations, were starting to become more commonplace, and surround-sound

recording and audio mixing was also becoming more popular. In 2016 the situation is very different – multi-channel impulse response convolution based reverberation effects are readily available in most common creative music software applications, and dedicated hardware devices are long since obsolete. It is now even possible to render an auralisation using a standard web browser on a mobile device. OpenAIR is one of many online resources for exploring the reverberation and acoustics of real and modelled spaces through the availability of impulse responses. What sets OpenAIR apart is the open-source data made available through a Creative Commons License, and that it supports multiple, uncompressed, high-resolution audio formats. The aim of this ongoing project is to survey, preserve, recreate and creatively apply the acoustic properties of the heritage spaces considered. To date these range considerably across period (Maes Howe, Orkney, dating from 2700BCE to the R1 Nuclear Reactor Hall in Stockholm, dating from 1970), size (from the few cubic metres of the Pozzelle di Pirro Zollino underground water system tanks to York Minster's approximate volume of 200,000m^3), reverberation time (0.4s at 1kHz for Troller's Gill limestone gorge in the Yorkshire Dales to 10s at 1kHz for the Terry's Chocolate Factory warehouse), and geography (Spokane Women's Club, Spokane, USA, to Koli National Forest Park, Finland).

OpenAIR has therefore become a central repository for our research in virtual acoustics and auralisation. It documents and disseminates high quality, spatially encoded impulse responses from buildings and landscapes around the world, as well as simulations from 3D computer models, and anechoic recordings suitable for preparing auralisations of these surveyed sites. In the fields of computer music, sound design and composition, the database has been incorporated under a Creative Commons License into leading digital audio workstations: *Properllerheads Reason*[6], *Presonus Studio One*[7] and *Ableton Live*[8]. These software applications are used in many aspects of modern music and audio production, enabling music composition, audio recording and manipulation, and performers to incorporate electronic music into their live work. A core component of any such software is the ability to apply reverberation modelling to source sounds, and this is now commonly implemented using convolution processing based on measured or modelled impulse responses sets. Hence music producers using such software are beginning to – perhaps unwittingly - explore the acoustics of the past through their appropriation of OpenAIR data. This research has also been used to deliver spatial impulse responses obtained from car cabins and audio assets for computer game sound design, and in 2014 the OpenAIR team were credited in the release of Codemasters' *Grid AutoSport*[9], in which this measurement work is featured.

4.1 Virtual Acoustics and Heritage: *Resounding Falkland*

The creative application of auralisation in heritage, however, continues to be a key application area for our virtual acoustics research. *Resounding Falkland* (Chapman and Wilson, 2011), was a collaboration with artists David Chapman, Louise K. Wilson and the Falkland Estate, Scotland, to explore how sound can be used to understand and interpret the history of existing landscapes.

This project resulted in a number of artistic outputs, sound based works - including a downloadable audiowalk to guide visitors through parts of the estate - installations and events. Acoustic surveys were completed for unusual or less well-known features of the Estate and surrounding landscape and the measurements obtained were then used, through analysis, to inform the artists' creative process, or directly, through auralisation, to produce new sound experiences. The sound of the waterfall cascades through the grounds of the House of Falkland were recorded and analysed, and a number of buildings were measured acoustically. These included the Tyndall Bruce Monument, a tall stone tower on a steep wooded path offering magnificent views over the Estate, that is, however, less well known and less accessible to the visitor than many of the Estate's other features. The Bottle Dungeon is another inaccessible space, a subterranean bottle shaped prison accessed via a trap door and narrow opening, leading to the wider open cell below. The entrance

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[6] https://www.propellerheads.se/reason
[7] http://studioone.presonus.com/
[8] https://www.ableton.com/
[9] http://www.gridgame.com/

to the Bottle Dungeon can now be found under a carpet in the administrators' office near the entrance to Falkland Palace. The acoustics of the semi-open and highly sound reflecting Falkland Real Tennis court - the oldest in the world still in use - were also captured.

The most significant challenge, however, was to create a 3D model and auralisation of the Temple of Decision, a now ruined structure on a hill overlooking the estate. Little is known about this nineteenth century folly, and although some documentary evidence exits, including photographs and drawings, no detailed plan could be sourced despite extensive research. The acoustic reconstruction was therefore informed by what could be discerned from the ruins that remain, the fragments of evidence that could be found, and what is known about the construction of similar buildings. This process of research and reconstruction was documented and reflected upon in the video installation *The Temple of Decision* (Figure 24), which includes the final auralisations produced from the 3D model. Perhaps the most notable aspect of this artistic work is not necessarily the final outcome – the model and accompanying auralisation – but the process by which this outcome has been determined, and the artists' personal experience of both the tangible and intangible aspects of this heritage landscape.

[temple_of_decision.mp4]

Figure 24: Temple of Decision is a video installation that investigated the ruin of the Falkland Estate's nineteenth century folly, part of which uses auralisation to recreate the acoustics of the building when still intact. The artists David Chapman and Louise K. Wilson voice their thoughts on visiting the Temple and on the stories they heard about the building and its uses. (Video © David Chapman and Louise K. Wilson, 2010, used with permission, 2016).

4.2 Virtual Acoustics and Virtual Reality: York Theatre Royal

York Theatre Royal is a regional producing theatre in the centre of York based on a site that has hosted a working theatre since 1744. It is built on the location of the 12th century St Leonard's Hospital, parts of which are still evident in the modern building together with the Georgian interior and a Victorian façade, in combination with more recent architectural interventions. Under the stage is a well that dates from the Roman period of York's history. In 2015 the theatre was subject to a major refurbishment, providing a unique opportunity to apply virtual acoustics research in a culturally and historically significant space as part of this process. To date this has involved the capture of impulse response and 360-degree image data, for various on-stage performer (sound source) and audience seating positions, and although most of this work took place outside of the normal rehearsal and production cycle, and hence an empty theatre, this did also include data capture during a production with a full audience in place. The acoustic measurement and data gathering process started in late 2014, and was completed by early 2015, before the refurbishment work started.

Creative applications for pre-refurbishment data have already being explored: Virtual Reality (VR) headset technology has allowed the combination of 360-degree images with immersive, binaural, head-tracked auralisation. Head-tracking is important to develop an immersive and plausible virtual reality experience so that the audio scene is updated as the subject's head moves, such that sound sources maintain their positions relative to each other and the orientation of the subject's head (compare, for instance, with standard stereo headphone listening where this does not take place). Hence it is now possible for a subject to experience a recorded performance from different seats in the house, and experience the sense of a theatre auditorium that no longer exists in this form. Virtual reality and auralisation combined enable new levels of creativity and opportunity to experience heritage and explore questions raised. One challenge relates to moving auralisation beyond the auditory sense to encompass rich visual assets via an immersive medium such as a VR-headset, and how we relate this to a sense of embodiment in the rendered scene. When viewing the stage of York Theatre Royal from a seat in the stalls, there is a sense of hovering somewhere above the seat itself. The percept matches our experience, yet when we look down we do not see our own body and nor can we interact with this scene with our own hands. Furthermore, theatre is usually a shared experience, yet such rendering places our virtual self in an empty

theatre space. The need for high quality acoustic measurement and image capture demands a controlled environment, yet produces a result very different from what a typical theatre-goer might expect.

Aside from considering questions such as these, our aim with this project is two-fold: to use acoustic heritage, auralisation and sound design to tell the story of the theatre space, and reveal the rich, multiple layers of its history; and to encourage new means of engaging with and accessing theatre performance - to develop new audiences, and deliver new experiences for those who already exist. York Theatre Royal reopened in April 2015 and this collaboration continues to explore how such digital assets might be deployed effectively to these ends. Further work on this project will involve post-refurbishment acoustic measurements and 360-degree image capture for the new auditorium space, and the development of an interactive, online, virtual York Theatre Royal auditorium explorer, to compare audio/visual experiences of a performance from different seats within the main house.

[figure25.jpg]

Figure 25: Acoustic measurement work in the pre-refurbishment York Theatre Royal auditorium: Genelec 8040 loudspeakers are used as virtual performers on stage, each of which will be a sound source for the impulse response measurements taken at various audience positions.

[figure26.jpg]

Figure 26: Acoustic measurement work in the pre-refurbishment York Theatre Royal auditorium: real performers are miked up and captured using 360-degee video cameras. The audio recordings made as part of this are used as the source material for a separate auralistion based on the measured impulse response measurements. Auralisation and 360-degree video are then combined to allow the user to select various audience locations and experience the final performance in immersive virtual reality from a number of different perspectives.

5. Acoustic Heritage and Experience

Although acoustic heritage in the context of this article has focussed on the development of an auralisation through a process of survey and/or modelling, our acoustic heritage does not have to be experienced only via headphones or loudspeakers. An adjunct to the OpenAIR project has been the question of how the spaces surveyed might be experienced directly in new or different contexts from the norm.

5.1 *I Hear Too*

In 2009, the *I Hear Too* project (Murphy and Brereton, 2012) set out to investigate how sound might be used to inform and transform our experience of heritage more generally, and one of the key aspects of this initiative was *I Hear Too Live* where York Minster was used as an acoustic canvas by a series of sound artists to explore their own creative practice. York Minster is an iconic building within the centre of York – a place for worship, tourism, music or theatrical performance, but rarely a place to be enjoyed in terms of its own unique and dramatic sound environment. Seven artists and the Ebor Singers choir were commissioned to respond to the acoustics of York Minster in whatever way they felt appropriate. This resulted in a range of audio experiences – mixed media video and sound in the quire, spoken word in the Zouche Chapel, whispered voices over multiple loudspeakers in the Chapter House, laptop musicians in the Nave, interspaced with bespoke performances from the Ebor Singers. The audience were encouraged to sit, explore, walk, listen and enjoy as they felt comfortable, resulting in a unique and memorable experience for all involved.

[figure27.jpg]

Figure 27: A visitor to I Hear Too Live listens to the whispered voices of David Chapman's 'Octo: Sotto Voce' installation in the Chapter House of York Minster (Figure 27 © Kippa Matthews, used with permission, 2016).

5.2 *Architexture I and II*

This idea for bespoke musical performance or event, specific to a given space, place and time resulted in *I Hear Too Live* being repeated, in both York Minster, and then in 2012 at the Guildhall and Mansion House buildings, also in York. In this latter example, a new piece, *Architexture I*, was commissioned from composer Ambrose Field for the Ebor Singers, designed for the specific acoustics of the Guildhall. Composers and musicians have always created music and performances for specific locations, but in this case, auralisation methodology was, for the first time, used as part of the process. Acoustic measurement was used to obtain a set of room impulse responses from the Guildhall that Field analysed in terms of reverberation time and frequency content, yielding information which was then used to optimise the melodic, harmonic and rhythmic content of the vocal lines, resulting in, what Field states, is, "precise and intricate connections between the musical material and the architecture of the venue", as quoted in (Murphy and Brereton, 2012).

This practice was developed further in 2015 for *Architexture II* (Field, 2015), another collaboration between Field and the Ebor Singers. This piece sees the natural development of Field's exploration of auralisation methodology, compositional practice and the experience of acoustic heritage. The site chosen in this case however, is a ruin and so acoustic measurement could not be used: St Mary's Abbey Church was closed and subsequently destroyed in 1539 as part of Henry VIII's dissolution of the monasteries. The remaining ruins are now part of Museum Gardens, York, giving a dramatic backdrop to this multi-use public park, and are the starting point of a 3D computer model that has been developed and optimised over a number of studies (Oxnard and Murphy, 2012) based on existing remains and additional third party scholarship and evidence (e.g. Wilson and Mee, 2009). The impulse responses obtained from the model were analysed and used by Field as part of the compositional process as before, but in this case there is no actual space available in which to hear the final work. Instead, *interactive auralisation* was used to render the sound of the reconstructed St Mary's Abbey Church as part of the actual performance. Based on the work of (Laird et al., 2014) and in particular the virtual singing studio developed in (Brereton et al., 2012), the members of the Ebor Singers wore head-set microphones to capture their natural vocal performance, with the results rendered and spatialised in real-time via multiple channels of convolution processing using the impulse responses obtained from the 3D model of the reconstructed space. *Architexture II* took place within the ruins of St Mary's, with the Ebor Singers singing live and the final auralisation played back over multiple PA-speakers to an audience of several hundred people, demonstrating a powerful example of how acoustic heritage and audio creativity together can provide a unique perspective and experience of aspects of our past.

[figure28.jpg]

Figure 28: The Ebor Singers perform Ambrose Field's 'Architexture II' within the ruins of St Mary's Abbey Church in Museum Gardens, York. Each singer wore a headset microphone and using interactive auralisation was able to sing their line, tuned carefully to the acoustic properties of the 3D model, through the reconstructed acoustics of the ruined space (Image © Ian Martindale Photography, 2015, used with permission 2016).

6. Conclusions

Exploring our acoustic heritage through auralisation and audio creativity significantly enhances the toolset of the digital heritage researcher, and is a powerful means of delivering memorable, meaningful, and most importantly, informed multi-sensory experiences. However, with the exception of the interactive techniques used for *Architexture II*, auralisation is only one particular, static, representation of how an environment sounds. It is a snapshot in time, for a fixed sound source and listener, and the final result depends greatly on the (known) limitations of the systems and techniques used as much as the design criteria applied.

When developing a model of any space the auralisation is only as good as the research into the source material documenting its provenance. If a space no longer exists, or only exists in part, it is not possible to state how accurate the final auralisation is – the result is only one point in an infinite set of acoustic possibilities, and it should ideally be accompanied with appropriate alternatives, and a full documentation of the process used to arrive at this set of end-points. In other case studies, where a site does in fact remain intact, and measurement may be seen to provide some certainty, it is important to have a good understanding of more recent ownership and use. Maes Howe is a particular example, as its current state is subject to the consequences of excavation, reconstruction and preservation that have taken place since 1861. The measurements we have, as documented on OpenAIR, are therefore not truly representative of a nearly 5000-year old Neolithic chamber tomb, but they do provide a clear acoustic description of its current state, and help to preserve this state as the site undoubtedly continues to change over future generations.

The final result achieved also depends on what it is about the auditory experience, that the acoustician, sound designer or artist desires the listener to perceive – immersive reality, plausible approximation or bold caricature? Perhaps most importantly, our perception of an auralisation reflects our own culture, our prior experience of sound events, and our sound environment, and this experience is contemporary to our own period, rather than that of any other. Our modern ears give us a unique and individually subjective experience of our acoustic world. It would be unwise to assume that this lends any particular authenticity to a digitally created, and ultimately general acoustic representation of the past, no matter how rigorous or accurate the methodology applied. What digital heritage research, auralisation and audio creativity do offer, however, is a more complete representation of this past, for the past was certainly not a silent place.

Future work in this area will see the continued development of the OpenAIR database, an online resource that is already delivering societal, cultural and potentially economic impact as these acoustic heritage assets become incorporated into creative workflows for music production and computer game sound design. As demonstrated with *Architexture I* and especially *Architexture II*, auralisation methodology, moving to live, real-time interactive auralisation, can deliver bespoke, significant and transformative experiences of our heritage to large audiences, while expanding the creative practice of the participants involved, from researchers and composers, through to performers and sound engineers. Also notable at time of writing is the considerable interest in the next generation of virtual reality headsets that are soon to be made more widely available commercially, and whose potential we are already exploring in our collaboration with York Theatre Royal. These headsets bring with them a demand for new and novel content, not just virtual reality versions of existing media, such as television, theatre, film and computer games, but new, and as yet unimagined, creative virtual reality experiences, defined by the potential of the medium, rather than the established norm. Of particular note is the research and development effort of significant parts of the VR industry to ensure that audio content supports the visual stimulus, combining head-tracking and enhanced spatial audio with these stereoscopic visuals to deliver an immersive and plausible virtual reality experience. Much of the spatial audio technology being exploited to enable this work is founded on the same research that has informed OpenAIR content for auralisation and virtual acoustics applications. If the next generation of consumer media is based on the creative application of virtual reality technology, OpenAIR assets, with the additional implication for the associated research and documentation of our acoustic heritage, are ready once again to be deployed in creative workflows to help deliver novel and memorable multi-sensory experiences.

Acknowledgements

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