ARCHAEOLOGICAL ACOUSTIC SPACE MEASUREMENT FOR CONVOLUTION REVERBERATION AND AURALIZATION APPLICATIONS

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ABSTRACT

Developments in measuring the acoustic characteristics of concert halls and opera houses are leading to standardized methods of impulse response capture for a wide variety of auralization applications. This work presents results from a recent UK survey of non-traditional performance venues focused in the field of acoustic archaeology. Sites are selected and analyzed based on some feature of interest in terms of their acoustic properties. As well as providing some insight as to the characteristics and construction of these spaces, the resulting database of measurements has a primary use in convolution based reverberation and auralization. A recent sound installation based on one of the selected sites is also presented.

1. INTRODUCTION

Convolution based reverberation and auralization for audio post-production and computer music applications require a large, high quality database of Room Impulse Responses (RIRs). The static nature of RIR based reverb/auralization does not lend itself to real-time editing of the virtual environment in the same manner as more established IIR filter/circulant-network based implementations. Hence, a larger database of virtual spaces is required to attempt to cater for every creative possibility. These RIRs must therefore be obtained through a process of either recording/measurement or modeling. Current research in capturing the acoustic characteristics of concert halls and opera houses is leading to standardized methods for carrying out high quality RIR measurements that are compatible with many different spatial audio auralization and rendering systems.

This paper presents results from a study of four selected archaeological sites in the UK, each demonstrating some feature of interest in terms of their acoustic characteristics. These sites do not necessarily come under the focus of current acoustic survey and measurement work in traditional music performance venues, but rather achieve their reputation and interest for other notable reasons.

The aim of this work therefore lies in a number of different areas. The primary aim is to expand the range of current acoustic measurement surveys to provide an increased palette of virtual spaces, particularly for practitioners in the fields of audio post production and sound design/composition. In a recent survey of concert halls and opera houses the importance of capturing the unique sound of these spaces and preserving them for posterity is highlighted as another valuable aim [1]. A similar study uses the acoustics of early music spaces to inform the design of modern concert halls [2]. This work also leads to the possibility of using archaeological/architectural acoustic analysis and spatial sound for the interpretation of important historical buildings or heritage sites. For the researcher such analysis may help to give further insight to the purpose of a site, its use or construction. The ability to audition and experience these sites via auralization will also help in the development of more rewarding and informative visitor interactives. This paper is organized as follows. In Section 2 the measurement techniques used for this study based on current best practice are defined, including surround-sound decoding and rendering options. Section 3 examines each of the four sites in turn and considers their relative acoustic characteristics, highlighting pertinent features appropriate for the interested convolution reverb user. Section 4 discuses how these techniques have been used to realize an audio-visual installation artwork and this paper is concluded with a summary of the work to date, and an indication of future directions for this measurement and research programme.

2. RIR MEASUREMENT SYSTEM

2.1. RIR Measurement Guidelines

There exist a number of prior studies that have explored methods for room acoustics measurement and impulse response capture. The CIARM group have written guidelines for measuring the acoustic characteristics of historical opera houses [3], using ISO3382 [4] as a reference. Recommendations include the use of omnidirectional sources exhibiting a wide, flat frequency response, with measurements recorded monaurally, binaurally and/or in B-format. The latter two approaches facilitate spatial analysis of the measured impulse responses. B-format recordings generally employ the use of the Soundfield Microphone, the output of which is four coincident signals corresponding to an omnidirectional sound pressure signal, W, and three figure-of-8 velocity responses, X, Y, and Z, directed as forwards-backwards, left-right and up-down respectively. With such a B-format measurement the W-component can be used for evaluating monaural acoustic parameters, and the additional directional signals to used evaluate spatial characteristics. The B-format signals can also be decoded for a wide variety of multi-channel surround-sound systems.

These guidelines have been developed and refined in more recent acoustic measurement work [2] especially that of Farina *et al.* [1], [5]. Two sound sources are also used, the first a small dodecahedral omnidirectional transducer, combined with a subwoofer, equalized to give a flat response between 80 Hz and 16 kHz. The second is a Genelec S30D, a three-way active multi-amped loudspeaker with AES/EBU digital input. Although it exhibits a more directional characteristic than the omni/subwoofer combination, its frequency response extends from 37 Hz to greater than 20 kHz with only ± 3 dB variation. The directivity pattern is also more consistent across this frequency range than the omni/sub combination, and avoids the associated errors present at higher frequencies due to the spacing and arrangement of the individual drivers. The microphones used comprise an ORTF cardioid pair, a binaural dummy head and a Soundfield ST-250 all arranged on an automated rotating turntable. The dummy head and the point of intersection of the ORTF pair are arranged at the centre of the turntable's axis of rotation.

2.2. Transducers, Signal Generation and Capture

Figure 1: *Measurement microphones mounted on a turntable and S30D sound source transducer.*

The main aim this project is for multi-speaker RIR auralization of the studied spaces. Hence, the need for binaural measurement is not of paramount importance although if required at a later stage it is possible to derive a binaural representation from a B-format signal. The chosen microphone combination is both a refinement and simplification of that used in [1] and is shown in Fig. 1. A 4-channel Soundfield SPS422B is positioned on a boom arm, 1m from the centre axis of an 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 pair spaced 17 cm apart at an angle of $110°$. Both microphones are set at a height of 1.5 m. A 15 s $22-22000$ Hz logarithmic sine sweep is used as the excitation signal via a Genelec S30D. This excitation-deconvolution technique has been shown to give better results than previously used methods in terms of signal-to-noise ratio, minimisation of harmonic distortion and not having to rely on repeated measurements and averaging for best results [6]. The rotating turntable is triggered automatically after each excitation sweep and measurements are made at $5°$ intervals over a complete $360°$ revolution. Typically, a single set of 72 measurements takes between 25–50 minutes depending on the reverberation time of the space being studied. Post-processing, deconvolution and objective parameter extraction from the resulting RIRs is carried out using Adobe Audition and the Aurora Plug-In Suite [7].

2.3. Decoding and Auralization

The 1 monaural + 4 B-format channels of RIR information can be combined for a wide variety of surround-sound rendering via an appropriate multi-channel audio convolution engine. Those most appropriate for this work are summarized as follows.

2.3.1. Stereo

ORTF stereo presentation for a source at angle θ is possible by selecting RIR pairs at $\theta \pm 55°$. The measurement method employed in this study enables ORTF stereo auralization via only one directional microphone rather than the two used in [1].

2.3.2. Ambisonic Decoding

It is possible to facilitate 2-D or 3-D first-order Ambisonic surround-sound decoding for a mono source to a regularly arranged speaker system of diametrically opposing pairs using the Soundfield B-format RIR channels. W, X, Y give 2-D horizontal decoding with W, X, Y, Z used for full 3-D surround-sound.

2.3.3. B-format derived 5.1 Surround

The B-format responses can also be used to derive discrete 5.1 surround-sound via virtual microphone array modeling. A number of possible microphone arrays have been suggested for recording in ITU 5.1 surround-sound, using combinations of spaced directional (usually cardioid) microphones. It is possible to process and combine the measured B-format RIRs at a specific angle θ to generate any first-order microphone directivity pattern according to (1) and (2) as presented in, for example [8]:

$$V(\alpha,\beta) = \frac{1}{2}\left[(2-d)\cdot W + d\cdot(r_x\cdot X + r_y\cdot Y + r_z\cdot Z)\right] \tag{1}$$

where:

$$\begin{cases} r_x &= \cos(\alpha)\cos(\beta) \\ r_y &= \sin(\alpha)\cos(\beta) \\ r_z &= \sin(\beta) \end{cases} \tag{2}$$

$V(\alpha,\beta)$ is the virtual microphone response, pointing in the direction of α, with elevation β, relative to angle θ around the central axis of measurement. W, X, Y, Z are the B-format RIRs in this case, and $0 \leq d \leq 2$ is the directivity factor where for instance $d = 0$ results in an omnidirectional response, $d = 1$ is a cardioid response and $d = 2$ is a figure-of-8 pattern. Using this method, virtual microphone responses at specific angular positions can be generated. These can then be used to simulate the equivalent discrete 5.1 spaced microphone array recording of a mono source in the measured space, offering an alternative auralization method to standard first order Ambisonic decoding.

2.3.4. High Order Spatial Decoding

Note also that other decoding schemes are also possible with additional post-processing, including higher order Ambisonic B-format according to Poletti's high directivity virtual microphones [9], Wave-field Synthesis [10], Spatial Impulse Response Rendering [11], as well as other hybrid approaches [8].

3. MEASUREMENT SITES

3.1. Acoustic Parameters

With a large database of RIRs available it becomes relatively straightforward to extract and analyze objective acoustic parameters to help quantify the characteristics of the measured spaces. The first parameter considered is ISO3382 T30 relating to the standard interpretation of *Reverberation Time* in octave bands and this is calculated and averaged from W-channel RIRs for angles $0°$, $90°$, 180° and 270°. The second parameter relates to the *Spatial Impression* of the space and there are a number of objective spatial measures that may be used to help characterize a space in terms of the perception of music heard within its walls, particularly with respect to how sound envelopes and surrounds a listener. *Inter Aural Cross Correlation* (IACC) is often used for binaural sound [12] and ISO3382 defines *Lateral Fraction*, LF [4]. LF can be derived from the W and Y channels of the B-format response, and [1] further defines a modified polar plot for the quantity '1-LF' which shows the angular variation of LF (strictly 1-LF) as it varies with the locus of movement of the Soundfield Microphone in this particular measurement arrangement. The results are directly comparable with standard IACC if it similarly varies with angle, and can be used to give a measure of the diffusivity of the space with high values for 1-LF (hence low values of LF) indicating a highly diffuse soundfield.

3.2. St. Andrew's Church, Lyddington

St Andrew's Church, built in the 14th Century, has one of the finest examples of in-situ acoustic jars (vases or pots) in the UK. These jars were common to European church construction in the late Middle Ages and are said to be based on the ideas of Roman architect Vitruvius, who discussed the use of resonant jars in the design of amphitheatres to provide clarity of voice presentation [13]. They are designed as Helmholtz resonators, giving narrow band energy absorption according to the natural frequency of the jar although there is little conclusive acoustical evidence to show that they behave as designed. Studies suggest that the success or otherwise of these devices depends on the number of jars used and their placement, as well as the characteristics of the building and jars themselves. A ratio of one jar to 120 m^3 is hypothesized as being a good example for success [14]. In anechoic and reverberant chambers the absorption effects of such jars are weak and highly selective, although can be significant below 200 Hz. Together with their additional diffusive effects, the jars potentially help to eliminate strong normal modes and hence can be made effective with careful tuning and positioning [15].

St Andrew's Church presents a good example for study with 11 jars placed high in the chancel, 6 in the north wall and 5 in the south, arranged at irregular intervals such that there are no directly opposite pairs. Although the total volume of the church (chancel + nave + aisles) is of the order of 2600 m^3, the chancel has a volume of only 700 m^3 giving a (Jar:Volume) ratio of 63 m^3, well within the ratio suggested in [14]. A detailed consideration of the jars present on this site as presented in [16] reveals they are clearly non-optimal in their construction, exhibiting weak Helmholtz resonance effects with any absorption that might be demonstrable locally not evident in more general source/receiver positions. There are also strong axial modes evident in the chancel space where the jars are situated, with the critical frequency of this part of the building being approximately 170 Hz. The natural jar resonances are between 350–470 Hz and are therefore beyond this region of modal dominance where they might have helped to absorb problematic axial modes between north and south walls as their placement possibly indicates.

3.2.1. Reverberation Time, T30

St. Andrew's is considered as having a "good" acoustic and is widely used by musicians and ensembles as a performance venue. Fig. 2 presents ISO3382 T30 values, calculated and averaged for the W-channel RIRs over angles 0°, 90°, 180° and 270°. The source was located at the altar steps in the chancel, with the microphone assembly placed in the nave giving a source-receiver distance of 11.5 m.

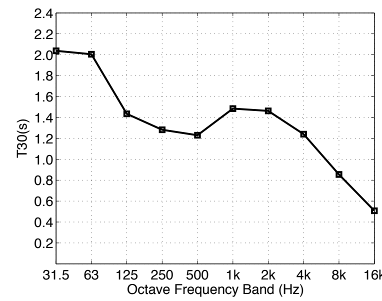

Figure 2: *IS03382 T30 value for St Andrew's Church W-channel RIR averaged over four measurement angles.*

Considering the 1 kHz T30 value of 1.5 s as a measure of reverberation time perception note the significant bass rise in the two lowest octave bands, potentially helping to support the bass end of musical material presented in the space and together with the gradual roll off in the high end giving a sense of perceived warmth. The dip in the lower mid-range will help with clarity of speech and single note melody lines.

3.2.2. Spatial Impression, 1-LF

Fig. 2 shows the polar plot for 1-LF calculated from the W and Y B-format responses at 10° increments, for a source placed at 0°. This result would indicate a reasonably diffuse space. Note that the 1-LF value is greatest directly to the front and rear demonstrating the coupled reverberant nature of the small chancel and the much larger nave, with most of the diffuse energy in the space arriving at the receiver from the rear (nave).

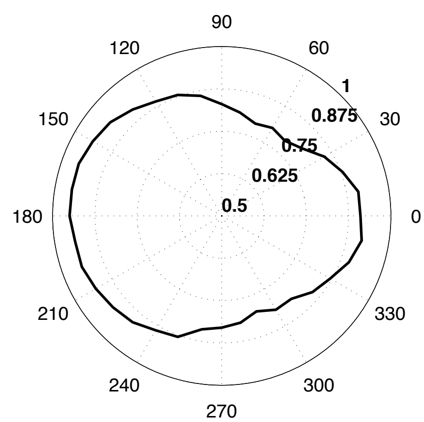

Figure 3: *(1-LF) polar plots for a source at* 0°.

3.3. Hamilton Mausoleum, Hamilton

Construction on the Hamilton Mausoleum, Hamilton, Scotland, built for the 10th Duke of Hamilton, started in 1842 and lasted until 1858. It is constructed of marble and sandstone and is surmounted by a dome 36m in height, with two main spaces, a crypt in the lower section, and a chapel that was supposed to be used for worship. However the construction materials, size, shape and dimensions of the latter result in a complex, dense and very long reverberation, and hence render it almost useless for speech presentation. In fact the Guinness Book of World Records claims that the Hamilton Mausoleum has the longest "echo" of any building [17], recorded on 27 May 1994 as taking 15 s for the sound of the reverberation caused by slamming one of the main doors to die away to nothing. The space is now often used by recording musicians for its unique acoustic properties. The interior of Hamilton Mausoleum is approximately octagonal in plan, with a diameter of 18 m. Each side of the octagon is either a plane wall or a further semicircular alcove. The results presented below having the microphone assembly in the centre and the source placed to one side, just outside one of the alcoves, giving a source-receiver distance of 4.8 m.

3.3.1. Reverberation Time, T30

ISO3382 T30 is calculated and averaged for the W-channel RIRs over angles $0°$, $90°$, $180°$ and $270°$ as shown in Fig. 4.

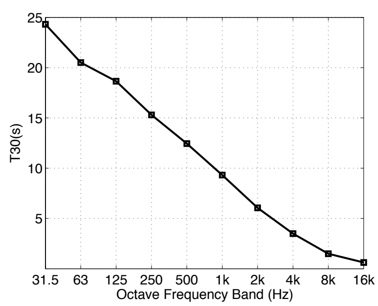

Figure 4: *ISO3382 T30 values for Hamilton Mausoleum W-channel RIR averaged over four measurement angles.*

The T30 values evident in Fig. 4 are clearly very dramatic, in excess of 20 s in the lower octave bands, falling almost linearly to 0.6 s at 16 kHz. Subjective listening confirms this, with the low frequency components for both the RIR in isolation and RIR/convolved audio lasting for some considerable time. Calculating T30 across the whole spectrum of the RIRs, rather than in octave bands gives a value of 15.0s — exactly that of the previously recorded "echo" duration. However, averaging over octave bands gives a value of 11.2 s, and the 1 kHz T30 value is 9.32 s, and these quantities perhaps give a more realistic measure of the perceived reverberation time.

3.3.2. Spatial Impression, 1-LF

Fig. 5 shows the polar plot for 1-LF calculated from the W and Y B-format responses at $10°$ increments, for a source placed at $0°$.

Note that there is a slight reduction in 1-LF at $140°$ and $240°$. This is due to two of the four flat wall sections of the Mausoleum's octagonal boundary, behind the microphone assembly when it is oriented at $0°$. These hard flat surfaces act to generate strong specular reflections towards the centre of the space possibly over a

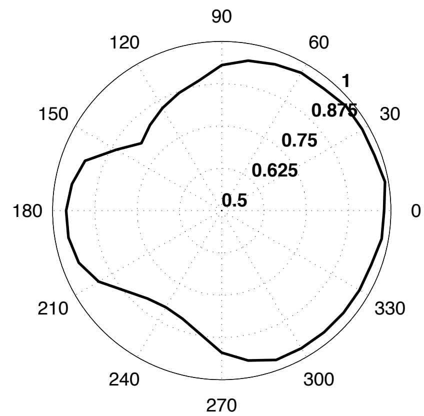

Figure 5: *(1-LF) polar plots for a source at* $0°$.

closed path due to the symmetrical nature of the construction. Potentially this could result in stronger lateral reflections incident on the Soundfield Microphone, hence a reduction in overall diffusion for these regions. Note that relatively the drop in 1-LF is small and the effect is not completely symmetrical as the wall section at $240°$ has a large rectangular marble sarcophagus placed in front of it.

3.4. Maes Howe, Orkney

Maes-Howe, Orkney, is one of the finest chambered cairns in Europe, dated to 3000BC. Prior work in the acoustics of ancient sites explores how the resonances exhibited therein might have affected regular human ritual and interaction with the space. For instance [18] presents results from six such sites, revealing strong standing wave patterns between 95–120 Hz with minimal azimuthal or vertical variation. It is hypothesized that as these resonances are within the lower male vocal range, they may have been used in ritual to accentuate aspects of the voice. Unlike many similar ancient structures that have been studied to date, Maes Howe lends itself to the presence of strong modal frequencies. It is almost cubic in shape, of dimension 4.6 m, with walls made from large, flat slabs of stone, resulting in smooth reflecting surfaces rather than more commonly found irregular placement of smaller stones.

3.4.1. Reverberation Time, T30

ISO3382 T30 is calculated and averaged for the W-channel RIRs as before, with the source located at the mid-point of the centre wall, and the microphone assembly in the centre of the space giving a source-receiver distance of 2 m. The results are shown in Fig. 6.

Note the rise in T30 for the 63 Hz and 125 Hz bands. Calculating T30 across the whole spectrum, rather than in octave bands gives a value of $0.55s$. Averaging over octave bands T30 $= 0.57$ s, and at 1 kHz T30 $= 0.51$ s. The rise to almost 0.9 s at 125 Hz is therefore significant and is due to the low frequency modal response, with strong peaks evident at 45, 90, 110, 120, 130 and 145 Hz [16].

3.4.2. Spatial Impression, 1-LF

Fig. 7 shows the polar plot for 1-LF calculated from the W and Y B-format responses at $10°$ increments, for a source placed at $0°$.

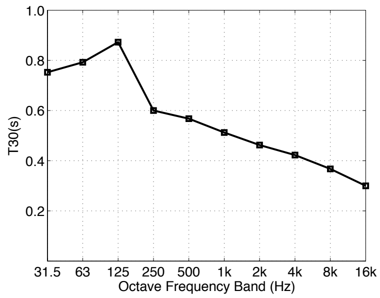

Figure 6: *ISO3382 T30 values for W-channel RIR averaged over four measurement angles.*

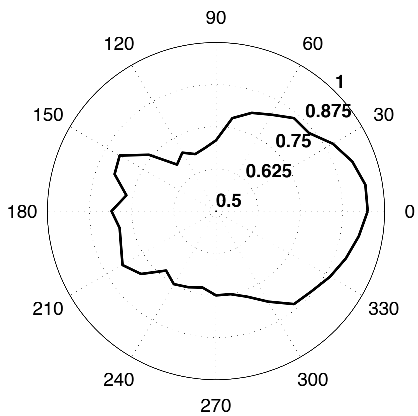

Figure 7: *(1-LF) polar plots for a source at* 0°.

These results indicate that this is a much less diffuse space compared with the other examples presented, and is to be expected given the small size and regular geometry of the chamber. There is also a general irregularity for 1-LF — the plot is less smooth as it varies with angle — due to dominant early reflections/direct sound present in this small space compared with late reverberation, reducing relative diffusivity according to angle of incidence at the receiver.

3.5. York Minster, York

York Minster is the largest medieval gothic cathedral in the UK and one of the finest in Europe, built between the 12th and 15th centuries on the foundations of the previous Norman church that was in turn constructed on the foundations of the original Roman fortress. It is approximately 160 m long, 76 m wide and 27 m high to the vaulted ceiling, constructed predominantly of stone with extensive, large panels of stained glass windows. Its beautiful acoustic and setting make it a sought after and highly popular music performance venue.

3.5.1. Reverberation Time, T30

ISO3382 T30 is calculated and averaged for the W-channel RIRs as before, with the source located directly under the centre tower, and the microphone assembly in the central nave area giving a source-receiver distance of 23.5 m. The results are shown in Fig. 8.

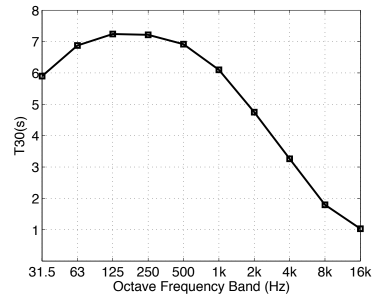

Figure 8: *ISO3382 T30 values for W-channel RIR averaged over four measurement angles.*

Note that the peak T30 value is 7.25 s in the 250 Hz band. Calculating T30 across the whole spectrum of the RIRs, rather than in octave bands gives a value of 6.4 s. Averaging over octave bands gives a value of 5.1 s, and the 1 kHz T30 value is 6.1 s.

3.5.2. Spatial Impression, 1-LF

Fig. 9 shows the polar plot for 1-LF calculated from the W and Y B-format responses at 10° increments, for a source placed at 0°.

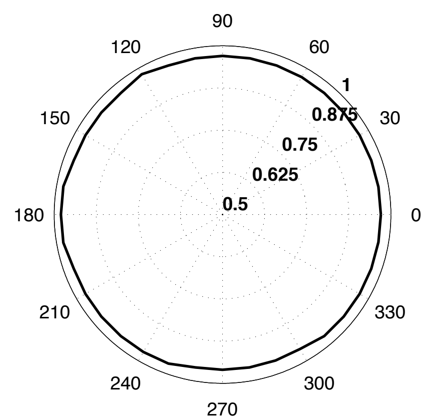

Figure 9: *(1-LF) polar plots for a source at* 0°.

York Minster is the largest of the presented spaces, with the greatest source-receiver distance (although still typical for music performances held here), and its construction and size result in long T30 values across octave bands. Hence, from Fig. 9 it is not surprising that the Minster demonstrates the highest level of diffusivity of all these results, being almost independent of direction, and hence demonstrating a high level of perceived spatial envelopment.

4. A SENSE OF PLACE

A Sense of Place is an interactive sound/light installation commissioned by the York Renaissance Project [19]. The artwork focuses on three specific aspects of York's 2000 year history interpreted using sound and light. The foundation of the piece is the Minster and what it has represented to York since the site was first used by the Romans. This has been realized using the Minster RIRs to render a virtual acoustic representation of this complex, diffuse reverberant space. The work is presented in one of the gatehouses on the city walls (Bootham Bar) transforming it from a small, enclosed space into a larger and more dramatic sounding virtual acoustic representation of the Minster. Further details about the project can be found at the accompanying online web resource [20].

5. CONCLUSIONS

This paper has demonstrated how developments in room acoustics measurement for auralization can be applied to the field of acoustic archaeology. RIR analysis can provide an insight to the characteristics and construction of these spaces, and the resulting database of measurements has a primary use in convolution based reverberation/auralization. The spaces examined all demonstrate some specific interest in their acoustics or construction. With the exception of the highly modal acoustics of Maes Howe, the sites demonstrate long T30 values and highly diffuse soundfields possibly limiting musical application of these RIRs to specific genres or post-production situations. Therefore it is important to continue to develop this RIR database, surveying a wider range of sites and extending the areas where these RIRs might be creatively applied. Selected RIRs will be available to the audio/computer music community as part of the UK Spatial Audio Creative Engineering research network (SpACE-Net) website [21] and will go live in September 2006.

6. ACKNOWLEDGEMENTS

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