Audio Objects Access: Tools for the Preservation of the Cultural Heritage

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Abstract. The digital re-recording of analogue material, in particular phonographic discs, can be carried out using different approaches: mechanical, electro-mechanical, opto-mechanical, and opto-digital. In this paper, we investigate the differences among these approaches, using two novel methods that have been developed on purpose: a system for synthesizing audio signals from still images of phonographic discs and a tool for the automatic alignment of audio signals. The methods have been applied to two case studies, taken from a shellac disc. Results point out that this combined approach can be used as an effective tool for the preservation of and access to the audio documents.

1 Introduction

The opening up of archives and libraries to a large telecoms community represents a fundamental impulse for cultural and didactic development. Guaranteeing an easy and ample dissemination of some of the fundamental moments of the musical culture of our times is an act of democracy which cannot be renounced and which must be assured to future generations, even through the creation of new instruments for the acquisition, preservation and transmission of information. This is a crucial point, which is nowadays the core of reflection of the international archive community. If, on the one hand, scholars and the general public have begun paying greater attention to the recordings of artistic events, on the other hand, the systematic preservation and access to these documents is complicated by their diversified nature and amount.

Within the group of documents commonly labeled audio analogue the sound recordings on discs are the most spread in the world from 1898 until about 1990. The common factor with this group of documents is the method of recording the information. This is by means of a groove cut into the surface by a cutting stylus and which is modulated by the sounds, either directly in the case of acoustic recordings (shellac 78 rpm discs) or by electronic amplifiers (shellac 78 rpm or vinyl discs). The wide time span in which these formats (with: different speed, number of audio channels, carrier chemistry characteristics) have been

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developed makes it even harder to select the correct playing format for each carrier. It should be clear the importance of transfer into the digital domain (active preservation), namely for carriers in risk of disappearing, respecting the indications of the international archive community (see [2,3,1] for some guidelines proposals and [26,5] for the ethics of the audio documents re-recordings). It is well-known that the recording of an event can never be a neutral operation, since the timbre quality and the plastic value of the recorded sound, which are of great importance in contemporary music (electro-acoustic, pop/rock, ethnic music) are already determined by the choice of the number and arrangement of the microphones used during the recording. Moreover, the audio processing carried out by the tonmeister is a real interpretative element added to the recording of the event. Thus, musicological and historic-critical competence becomes essential for the individuation and correct cataloguing of the information contained in audio documents. The commingling of a technical and scientific formation with historic-philological knowledge also becomes essential for preservative re-recording operations, which do not coincide completely with pure A/D transfer, as it is, unfortunately, often thought.

The increased dimensionality of the data contained within an audio digital library should be dealt with by means of automatic annotation. The auditory information contained in the audio medium can be augmented with cross-modal cues. For instance, the visual and textual information carried by the cover, the label and possible attachments has to be acquired through photos and/or videos. The storage and representation of this valuable information is common practice and is usually based on well-known techniques for image and video processing, such as OCR, video segmentation and so on. We believe that it is interesting as well, even if not studied yet, to deal with other information regarding the carrier corruption and imperfection occurred during the A/D conversion. After a detailed overview of the debate evolved since the Seventies inside the archivist community on the audio documents active conservation (Sec. 2), this work describes different approaches for re-recording of phonographic discs (Sec. 3) and a tool to align the different audio signals (Sec. 3). Sec. 5 provides two case studies where the similarities and differences of the approaches to re-recording are highlighted. A number of applications are described in the concluding section.

2 Audio Archivists: A Discussion 30 Years Long

A reconnaissance on the most significant positions of the debate evolved since the Seventies inside the archivist community on the audio documents active conservation, points out, at least, three different points of view [23], described below.

2.1 William Storm

William Storm [27] individuated two types of re-recording which are suitable from the archival point of view: 1) the sound preservation of audio history, and 2) the sound preservation of an artist. The first type of re-recording (Type I) represents a level of reproduction defined as the perpetuation of the sound of an original recording as it was initially reproduced and heard by the people of the era. The second type of re-recording (Type II) was presented by Storm as a more ambitious research objective: it is characterized by the use of playback equipment other than that used originally with the intent of obtaining the live sound of original performers, transcending the limits of a historically faithful reproduction of the recording.

2.2 Dietrich Schüller

Schüller in [26] and in [5] points directly towards defining a procedure which guarantees the re-recording of the signals best quality by limiting the audio processing to the minimum. He goes on to an accurate investigation of signal alterations, which he classifies in two categories: (1) intentional and (2) unintentional. The former include recording, equalization, and noise reduction systems, while the latter are further divided into two groups: (i) caused by the imperfection of the recording technique of the time (distortions), and (ii) caused by misalignment of the recording equipment (wrong speed, deviation from the vertical cutting angle in cylinders or misalignment of the recording in magnetic tape). The choice whether or not to compensate for these alterations reveals different re-recording strategies: (A) the recording as it was heard in its time (Storm's Audio History Type I); (B) the recording as it has been produced, precisely equalized for intentional recording equalizations (1), compensated for eventual errors caused by misaligned recording equipment (2ii) and replayed on modern equipment to minimize replay distortions; (C) the recording as produced, with additional compensation for recording imperfections (2i).

2.3 George Brock-Nannestad

George Brock-Nannestad [6] examines the re-recording of acoustic phonographics recordings (pre-1925). In order to have scientific value, the re-recording work requires a complete integration between the historical-critical knowledge which is external to the signal and the objective knowledge which can be inferred by examining the carrier and the degradations highlighted by the analysis of the signal.

2.4 Guidelines for an Audio Preservation Protocol

Starting from these positions, we define the preservation copy as a digital data set that groups the information carried by the audio document, considered as an artifact. It aims to preserve the documentary unity, and its bibliographic equivalent is the facsimile or the diplomatic copy. Signal processing techniques are allowed only when they are finalized to the carrier restoration. Differently by the Schüller position, it is our belief that in a preservation copy only the intentional alterations (1) must be compensated (correct equalization of the re-recording system and decoding of any possible intentional signal processing interventions). All the unintentional alterations (also the ones caused by misalignments of the recording equipment) could be compensated only at the access copy level: these imperfections/distortions must be preserved because they witness the history of the audio document transmission. The A/D transfer process should represent the original document characteristics, from either information and material points of view, as it arrived to us. According to the indications of the international archive community [2,3,1,16,15,17]: 1) the recording is transferred from the original carrier; 2) if necessary, the carrier is cleaned and restored so as to repair any climactic degradations which may compromise the quality of the signal; 3) re-recording equipment is chosen among the current professional equipment available in order not to introduce further distortions; 4) sampling frequency and bit rate must be chosen with respect to the archival sound record standard (at least, 96 kHz / 24 bit, adopting the guideline: the worse the signal, the higher the resolution); 5) the digital audio file format should support high resolution, it should be transparent with simple coding schemes, without data reduction. It is important to highlight that this protocol fits very well in the ontology approach used in [21,22] developed in the field of digital object preservation describing its internal relationships to support the preservation process. The ontology is an extension of the CIDOC Conceptual Reference Model (CIDOC-CRM), which is an ISO standard for describing cultural heritage [11,12,14].

3 Phonographic Discs Re-recording Systems

Four typologies of playing equipment exist.

Mechanic. It uses a mechanical phonograph, the most common device for playing recorded sound from the 1870s through the 1950s, where the stylus is used to vibrate a diaphragm radiating through a horn.

Electro-mechanical. Turntable drive systems, configured for use with a pickup: (1) piezo-electric crystal (where the mechanical movement of the stylus in the groove generates a proportional electrical voltage by creating stress within a crystal); (2) magnetic cartridges, moving magnet or moving coil. Both operate on the same physics principle of electromagnetic induction.

Opto-mechanical. A laser turntable is a phonograph that plays gramophone records using a laser device as the pickup, rather than a conventional diamond tipped stylus [18]. This playback system has the advantage of never physically touching the disc during playback. The laser pickup uses five beams one on each channel to track the sides of the groove, one on each channel to pick up the sound (just below the tracking beams), and a fifth to track the surface of the record and keep the pickup at a constant height, which compensates for record thickness and any warping. The lasers focus on a section of the groove above the level where a conventional stylus will have traveled, and below the typical depth of surface scratches, giving the possibility of like-new reproduction even from worn or scratched records. Using a laser pickup reduces many problems associated with physical styli: horizontal tracking angle error, leveling adjustment issues, channel-balance error, stereo crosstalk, anti-skating compensation, acoustic feedback, problems tracking warped, and cartridge hum pickup. Unfortunately, the laser turntable is, however, extraordinarily sensitive to record cleanliness. Moreover, when a phonographic disc is inserted into the tray drawer and the drawer closed, the turntable reads the surface of the disc, displaying the number of tracks: the record must be black or opaque-colored; transparent or translucent records may not play at all. The laser turntables are constrained to the reflected laser spot only and are susceptible to damage and debris and very sensitive to surface reflectivity. National Library of Canada and, since 2001, the Library of Congress in Washington DC used also this system.

Opto-digital. Nowadays, automatic text scanning and optical character recognition are in wide use at major libraries: unlike texts, A/D transfer of historical sound recordings is often an invasive process. Digital image processing techniques can be applied to the problem of extracting audio data from recorded grooves, acquired using an electronic camera or other imaging system. The images can be processed to extract the audio data. Such an approach offers a way to provide non-contact reconstruction and may in principle sample any region of the groove, also in the case of a broken disc. These scanning methods may form the basis of a strategy for: a) larger scale A/D transfer of mechanical recordings which retains maximal information (2D or 3D model of the grooves) about the native carrier; b) small scale A/D transfer processes, where there are insufficient resources (trained personnel and/or high-end equipments) for a *traditional* A/D transfer by means of turntables and A/D converters; c) the active preservation of carriers with heavy degradation (breakage, flaking, exudation). In literature there are several approaches to this problem (see [13,9,28]).

The authors have developed a system (Photos of GHOSTS: *PoG* [7]): a) able, automatically, to recognize different rpm and to perform tracks separation; b) works with both low-cost hardware and not-trained personnel; c) is robust with respect to dust and scratches; d) outputs de-noised and de-wowed audio, by means of novel restoration algorithms. An equalization curve choice by the user is possible: the system has hundreds of curves stored, each one with appropriated references (date, company, roll-off, turnover). Moreover, *PoG* allows the user to process the signal by means of several audio restoration algorithms [8,4]. The

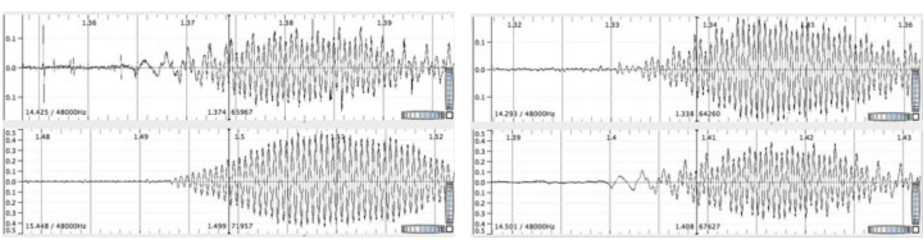

Fig. 1. Waveforms of the audio signals taken with the four re-recording systems of *La signorina sfinciusa*: turntable (top-left); phonograph (bottom-left); laser (top-right); PoG (bottom-right)

system uses a customized scanner device with rotating lamp carriage in order to position every sector with the optimal alignment relative to the lamp (coaxially incident light). The software automatically finds the record center and radius from the scanned data, for performing groove rectification and track separation. Starting from the light intensity curve of the pixels in the scanned image, the groove is modeled and, so, the audio samples are obtained.

Fig. 1 shows a comparison of the waveforms of the audio signals extracted by means of the described equipments (excerpt of *La signorina sfinciusa*).

4 Audio Alignment

Audio alignment is normally used to compare the characteristics of different performances of a music work. The goal is to find, for each point in one performance, the corresponding point in the second performance. This information can be useful to highlight differences in expressive timings, such as the use of rallentando and accelerando, and the duration of notes and rests which can be modified by the performers. A graphical representation of the alignment curve, which matches pairs of points in the two performances in a bi-dimensional representation as shown in Fig. 2, gives a direct view of the main differences between the styles of two performances [10]. Alignment can be applied also to different versions of the same recording. For instance, in the case of electro-acoustic music, recordings published at

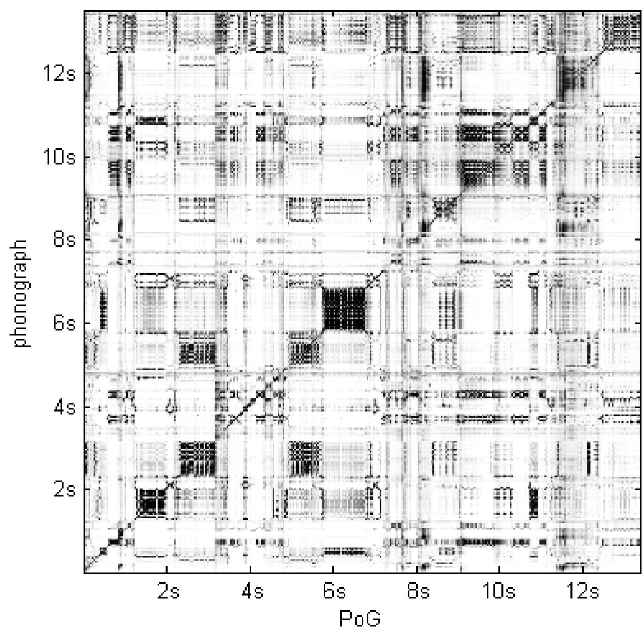

Fig. 2. Graphical representation of the local distance matrix. X-axis: the audio signal synthesized by PoG system; y-axis: audio signal extracted by means of phonograph.

different times may have undergone different post processing and editing phases [24]. In this case, alignment may highlight cuts and insertions of new material in the recordings, which may be difficult to detect manually, showing the usage of previous released material inside a new composition.

We propose to apply alignment techniques to compare the re-recordings of a disc with the one obtained through the technique based on digital images described in the previous section. For instance, it is likely that the recording speeds differ slightly depending on the quality of the analogue equipment. Moreover, there can be local differences in sound quality due to a different sensitiveness to possible local damages on the record surface. Once the two recordings have been aligned it is possible to compare their sound quality in corresponding points, in order to assess objectively the quality of the re-recording. The comparison can be used to estimate which kind of equipment has been used for the analogue re-recordings, in the common case this information has not been maintained. Moreover, point to point comparison highlights critical parts of the recordings, where the effect of damages is more relevant, giving indications on how to precede with possible digital restorations.

In order to be aligned, the recordings have to be processed to extract relevant features that capture the most relevant acoustic characteristics. The representations are then aligned by computing a local distance matrix between the two representations and by finding the optimal global path across this matrix. A popular approach to compute the global alignment is Dynamic Time Warping (DTW), that have been developed in the speech recognition research area [25] and applied, together with other techniques such as hidden Markov models, to audio matching [19,20,10]. As the name suggests, DTW can be computed efficiently using a dynamic programming approach.

The first step thus regards the choice of the acoustic parameters that are to be used. Given the relevance of spectral information, the similarity function is normally based on the frequency representation of the signal. After a number of tests, we choose to focus on frequency resolution, using large analysis windows of 8192 points with a sampling rate of 48 kHz, using an hopsize between two subsequent windows of 4096 points. With this parameters, each point to be aligned corresponds to an audio frame of about 0.17 seconds, while the time span between two subsequent points is 0.08 seconds. After choosing how to describe the digital recordings, a suitable distance function has to be chosen. We propose to use the cosine of the angle between the vectors representing the amplitude of the Fourier transform, which can be considered a measure of the correlation between the two spectra. Thus, given two recordings f and g, the local distance $d(m,n)$ between two frames can be computed according to equation

$$d(m,n) = \frac{\sum_{i=1}^{K} F_m(i)\ G_n(i)}{\|F_m\|\ \ \|G_n\|} \tag{1}$$

where $F_m(G_n)$ is the magnitude spectrum of frame $m(n)$ of recording $f(g)$, while in our application $K = 8192$ points. Local distance can be represented by a distance matrix, as shown in Fig. 2, where the main similarities are along the diagonal with large dark squares correspond to long sustained notes and brighter areas represent a low degree of similarity between two frames. In order to reduce computational cost, the local distance needs to be computed only in proximity of the diagonal.

After the local distance matrix is computed, DTW finds the best aligning path computing the cumulative distance $c(m, n)$ between the two recordings. We chose to force the global alignment to involve all the frames of both signals, so that for each frame in one of the recordings there is at least one corresponding frame in the second. In this way it is possible to compare the acoustic characteristics of any couple of recordings, for instance assessing how different analogue equipments are robust to a particular damage, highlighting its effect in the frequency representation.

5 Case Studies

As case studies we selected two shellac discs, which :

- Pasquale Abete, *Fronne 'e limone* (the term "fronne 'e limone" represents a popular music genre from Southern Italy), recorded in New York in May 1921, thus it is a mechanical recording and it has been played at 80 rpm.
- Leonardo Dia, *La signorina sfinciusa* (The funny girl), recorded in New York on the 24th July 1929, in this case, because it was an American electric recording it has been played at 78.26 rpm.

The audio signal was extracted in four ways:

1. mechanical: phonograph His Master Voice, Monarch model, equipped with a pickup HMV Exhibition and a horn Columbia. The re-recording was carried out in a $4m^2$ room; the signal was recorded by means of a cardiod microphone Rhøde NT23, installed in parallel to the horn axis, 7.5 cm away and central respect to the horn. The microphone was set in semi-cardiod position, in order to compensate the room reverberation. A balanced wire transmitted the analogue signal to a A/D portable board Motu 828 MkII, where it is transferred in the digital domain, with a 48 kHz sample rate and a 24 bit resolution.
2. Electro-mechanical: turntable Diapason model 14-A with arm Diapason, pickup Shure M44/7, Stylus Expert. The setting was: 78.26 rpm; 3.5 mil; 4g; truncated elliptical; FFRR equalization curve. Prism A/D Converter Dream AD-2.
3. Opto-mechanical: player laser ELP mod. LT-1XRC. The setting was: 78.26 rpm, FFRR equalization curve. Prism A/D Converter Dream AD-2.
4. Opto-digital: PoG system, with a photo taken at 4800 dpi, 8 bit grayscale, without digital correction.

The four periodograms of the audio signals of the first case study, shown in Fig. 3, highlight that, even if turntable and laser are more sensitive, both to the

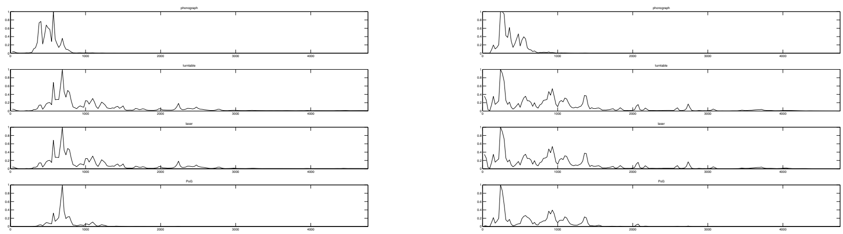

Fig. 3. Periodograms of the audio signals (about 20 seconds each) taken with the four re-recording systems of *Fronne 'e limone* (left) and *La signorina sfinciusa* (right)

original signal and to the artifacts (scratch and dust) on the carrier, the four systems give comparable results. A closer analysis of the turntable spectrum, showed a peak at about 11 Hz, which is due to the mechanical vibrations of the arm and probably to a resonance between the arm and the engine. The same peak is not observed in the three other spectra. Similar considerations apply to the second case study.

The method described in Sec. 4 was used to evaluate differences and similarities between these audio signals. At first we compared the playback speed of the mechanical equipment with PoG, which is a useful reference because it is not subject to mechanical variations. For the two case studies, we noticed that all the systems had constant speed, with no variation from the nominal value. Fig. 2 highlights this regular trend for the phonograph.

We also computed and aligned the most relevant features proposed in the audio processing literature. In particular, the first four spectral moments (centroid, spread, skewness, and kurtosis), brightness, and spectral rolloff have been computed using an analysis window of 8192 points (all the signals were sampled at 48 kHz, 24 bit resolution). As it can be noted from Fig. 4, spectral rolloff is a good indicator for highlighting the use of a phonograph, because the rolloff values are very close to the ones given by PoG. Moreover, we computed mean and variance of the point to point differences of brightness values, using PoG as

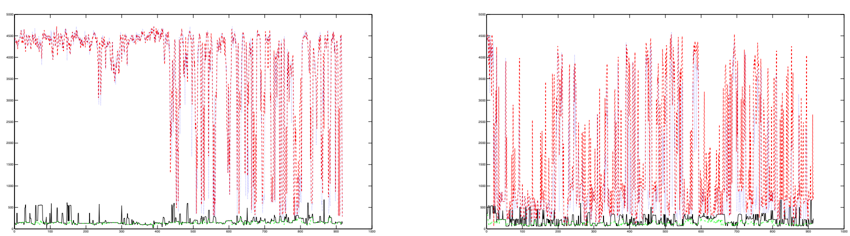

Fig. 4. Rolloff of the audio signals taken with the four re-recording systems of *Fronne 'e limone* (left) and *La signorina sfinciusa* (right): phonograph (green, dash-dot), turntable (red, dashed), laser (blue, dotted), and PoG (black, solid)

Table 1. Mean and variance of the difference between brightness of three re-recording systems using PoG as a reference

Case Study	Equipment	Mean	Variance
Fronne 'e limone	phonograph	0.158	0.611
Fronne 'e limone	turntable	0.024	0.713
Fronne 'e limone	laser	1.734	1.647
La signorina sfinciusa	phonograph	-0.467	1.167
La signorina sfinciusa	turntable	-0.420	0.974
La signorina sfinciusa	laser	0.182	0.600

a reference. Results in Tab. 1 show that, at least with the two case studies, it is possible to use the mean difference between the turntable acquisition and PoG in order to distinguish it from the laser acquisition.

6 Conclusions

Audio archivists can take advantage from a variety of equipments for the re-recording of phonographic discs. We presented two case studies using four different paradigms: mechanical, electro-mechanical, opto-mechanical, and opto-digital. Although there are some differences on the sensitiveness in respect to either the audio signal and to the corruptions, the four approaches give comparable results. The choice of the system depends on the aims of the audio archive, as described in Sect. 2, but is also biased by the resources (human and economical) that are available for the A/D transfer task. The results of this study suggest different directions.

A federation of libraries may have a number of different digital versions of the same material, and metadata may describe neither the A/D transfer nor the link to the original carrier. By applying the procedure described in this work, that is synthesizing an audio signal using *PoG* and aligning it to the existing digital documents, it is possible to identify the kind of A/D process, its eventual defects, and retrieve the original analogue recording.

It is common practice for large archives to store digital images of the carriers. Given the reduced costs of mass storage, it is likely that also high quality pictures are stored in the archive and used by *PoG*. Our approach can be exploited for monitoring the quality of A/D transfer, by using objective measures for checking playback speed, detecting missing samples or digital tick, and equalization curves. Monitoring can be carried either on already transferred documents or during the A/D process.

For smaller archives, which cannot afford the personnel and technological costs, our results show that preservation copies can be created using only high resolution photos. The access copy can be synthesized on demand using *PoG*, or similar approaches developed in the meanwhile.

Finally, if the disc is a unique copy of historical recordings, an opto-digital approach allows us to listen to the document (and create a preservation copy) in a non invasive way (i.e. without the use of some kind of adhesive) also when the carrier is seriously damaged so that alternative re-recordings are unfeasible.

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