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Challenges in Optical Recovery of Otherwise Unplayable Analogue Audio Disc Records

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ABSTRACT

Though limited to monophonic playback, the INA-Saphir analogue disc recording optical playback system is applicable to a wide range of grooved disc records, from earliest lateral and vertical-cut shellacs to recorded letters, from glass-based discs with missing chunks to thin transparent dual-side records and phonocards. The effort required for playing a disc side mostly depends on the number of cracks or missing parts. The current operating mode consists in delegating to a software solver the identification of the best path across all the groove track fragments, manually adjusting the details, and iterating until the satisfying solution is found. This process, from straightforward on records with few cracks, may spill over several days when extracting in parallel the full contents of several records with many wide cracks.

The achievable quality is quite variable, very much dependent on the reflectivity of the groove walls. When the condition of the record does not allow wet cleaning, dry cleaning is still often possible. Dry-cleaning using roller brushes is applicable to removing the largest part of lacquer plasticizer exudates. In the case of de-laminating lacquer flakes, a hand-held soft motorized rotary brush can still be applied by maintaining the lacquer flakes in place with a hand-held soft window, and re-positioning the flakes before scanning under a glass pane.

The scanner is compact, similar in size to most conventional turntables, still can accommodate up to 17 Inch discs, and allows recovering audio signals up to 20kHz. It can be moved easily, and can be operated without complex setup. Improvements on the software are still underway, but the system can already be replicated and made available to audio archives and service providers.

1 Introduction

Digitizing grooved audio discs is necessary to make available the audio recordings for listening and analysis. Despite it involves a physical contact, conventional playback using a stylus is still the main way of performing digitization. However, optical approaches allow for digitization without contact with the groove wall. The main drawbacks of optical playback are slowness, a frequent loss of quality, and complex setups. But the main advantage lies in the reduced risk for the disc and for the equipment. We will principally focus here on the many disc records that cannot be played using a stylus: first and foremost cracked, broken, and de-laminating lacquer discs, but we will also explore other cases, such as shellacs, dictation discs, phonocards, voice letters, masters and molds, and others, in varied condition.

2 Operative optical playback tools for grooved records

A number of tools for optical playback of grooved discs were proposed and developed, since at least 1929, as identified by Brock-Nannestad [1]. Most of the actual implementations are detailed in [2]. At the time of this writing, we only know of 4 processes that are in exploitation. Those processes are summarized below.

The *ELPJ* laser player [3] uses the reflective properties of the groove walls to measure in real time the direction of reflected laser rays, giving excellent results on vinyl records in pristine condition. It has been a commercial product since at least 1998. It is however not suitable for discs in poor condition [4].

Irene is a suite of tools for measuring the groove. The first implementation Irene-3D [5] uses con-focal microscopy to digitize in 3D the record surface and groove, with sufficient accuracy to extract the audio signal embedded in the groove. The second implementation Irene-2D [6] exploits a monochrome 1.4µm-resolution camera setup to image the disc surface. The groove top and bottom positions are then extracted, and analyzed to extract the audio signal. Irene-3D performs better on depth-cut (hill-and-dale) disc and cylinder records, whereas Irene-2D is more adapted to lateral-cut disc records.

The *VisualAudio* process [7], [8] is based on a photographic process where a 1:1 scale negative photography of the disc is taken. After development, the picture is scanned using a monochrome 2.5µm-resolution camera setup. The resulting strips are analyzed in a way similar to Irene-2D.

Our *INA-Saphir* process [2], [9] uses a color-coding condenser and the reflective properties of the groove wall to generate color coded pictures. The measured colors give a direct indication of the audio signal, at a 4µm resolution, enough for a 0-20kHz bandwidth.

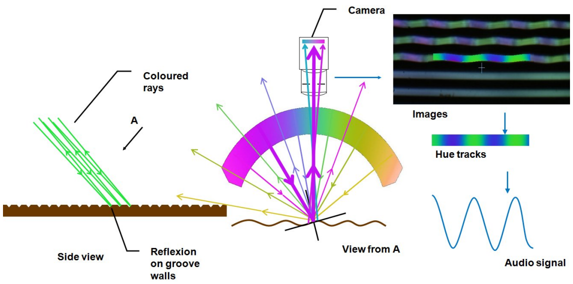

Figure 1: The INA-Saphir color-based process

Overlapping pictures are assembled into a ring, and overlapping rings cover the recorded area. The INA-Saphir software then tracks the groove wall within the pictures, converts the measured colors into audio signals, and generates audio fragments positioned on a map of the disc. A solver is used to identify the best path between fragments for playback. In complex cases, operator involvement is needed to adjust the parameters of the best-path problem.

3 Cracked and broken records

The main reason why we started developing INA-Saphir was – as the French radio archive – INA had in their own collections some 276,000 disc records, mostly direct-recording lacquer discs, recorded between 1930 and 1958. Lacquer records take their name from their constitution, as a core made of aluminum, zinc, glass, sometimes cardboard, covered with a thin coat of lacquer paint, as detailed by Rochat [10]. The audio signal is recorded as a groove cut or embossed into a fraction of the thickness of the lacquer. Monophonic audio signals are usually laterally (i.e. radially) recorded, less often vertically. The audio signal (air pressure) is translated into the cutter velocity.

Lacquer aging results in the lacquer losing part of its volume through out-gassing and exudation [10]. Part of this loss results in thickness reduction, but the lacquer also tends to contract, increasing tension when the – more stable – core does not allow it. When the resistance limit is reached, the lacquer coating cracks, often at the bottom of one groove sector, or radially. On most aluminum-based lacquer records, as the one in Figure 2, the resulting lacquer fragments still adhere to the aluminum surface. But other types of core, and specifically zinc-based cores

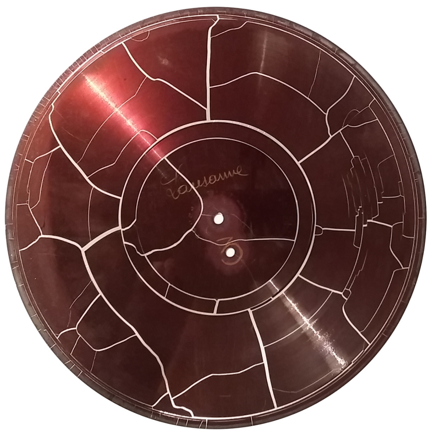

Figure 2: A wide-cracked 30cm aluminum-based lacquer record disc

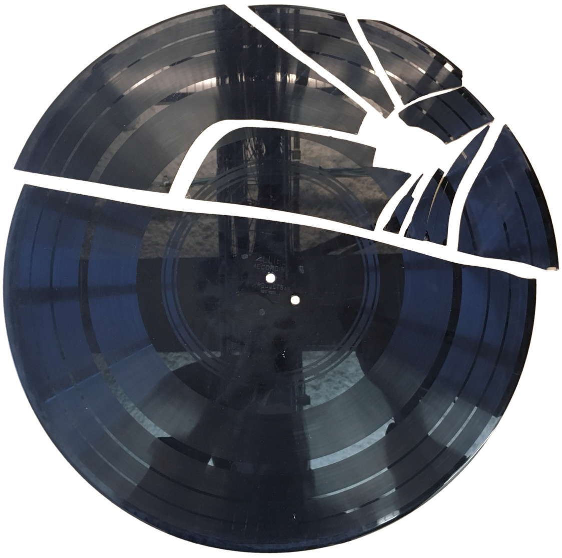

Figure 3: A 40cm glass-based broken lacquer record with missing parts

develop oxidation below the lacquer surface, resulting in a much lower adhesion between lacquer and core. When the lacquer starts cracking, most of it starts peeling off from the zinc as lacquer flakes with curly edges. The case of glass-based lacquer discs is specific; lacquer adhesion is usually fair, but the core is very fragile, as most of the glass cores are 1mm thick only. Any excessive constraint, shock, of pressure point can break the disk into several pieces, as shown in Figure 3.

Except in rare situations, lacquer cracks and broken records make mechanical playback impossible, due to the risk of damaging the stylus and the disc, and the difficulty in reordering the correct playback sequence of the groove fragments.

Optical playback of cracked and broken record does not endanger the playback head or the record, and offers routes to playing back the grove fragments in the correct order. INA-Saphir currently makes few assumptions on the existence of lacquer flakes, but rather gives the operator the opportunity to reconnect whatever groove fragments can be read using the optical pickup head. The fragments are first cut following a cracks detection map generated by a procedure obtained through machine-learning. The solver then finds a solution to a routing problem, where long jumps are penalized, but where using as much as possible of the available groove fragments is rewarded. The operator has nevertheless to ensure that the right routing problem is submitted: accidental remaining bridges across

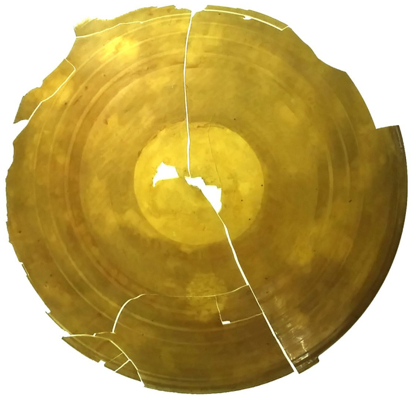

Figure 4: A broken transparent-yellow dictation disc, 0.5mm thick, recorded on both sides

cracks have to be cut, and all the necessary jumps have to be available. Therefore the correct path is usually not found on the first attempt.

When only a few thin cracks are present, a few attempts are usually sufficient. When there are very wide cracks or when lacquer flakes overlap, a high number of trials may become necessary, making this process all but fast. But the method is applicable even to records in a very poor condition, even in the case of missing parts.

4 A vast variety in constitution and condition of grooved record discs

4.1 Colored and discolored discs

A very comprehensive review of lacquer record discs in various conditions was produced by Rochat [10]. A significant part of those records are not black, but exhibit different colors. Sometimes the color is original (red, blue, green…); often the initial black has acquired a reddish or greenish tint, or has become mostly transparent, with a greenish of yellowish tint. We have also met yellow transparent thin and fragile disc records, possibly used in dictation machines, such as the one in Figure 4.

It was initially expected that INA-Saphir would not be able to play discolored and transparent discs, and we were surprised that a simple adjustment of the R, G, and B gains did allow a successful tracking and signal extraction from those records. The transparency of the medium may however present undesirable effects, e.g. on the thin transparent dual-side records, where the groove recorded onto the other side may still be visible through the medium, sometimes generating undesirable read-through. In some cases we had also problems on finely-cracked

Figure 5: A zinc-based de-laminating lacquer disc record with lacquer curling and missing patches

records when multiple internal reflections would spoil the pictures and the audio signal.

4.2 Warped lacquer, warped records

Lacquer adhesion problems can make optical reading challenging. Sometimes the lacquer flakes are curled on the edges, sometimes the whole lacquer surface has become curly. When trying to play back optically, two problems arise.

First, the whole height of the curl may not fit within the optical pickup head depth of field. In our case we have a depth of field of some 0.3mm. For curls that would rise above this limit, the resulting picture content would be blurred. Adaptive pickup height was considered, but not implemented. We have rather adopted a crude strategy, using a glass pane to keep the lacquer flakes flat enough so that most of their surface would fit within the pickup head depth of field. This is not really contact-less, but has a number of advantages, as it does protect the lacquer fragments from dust and from accidentally being blown away during the scan.

Second, as INA-Saphir best angle for capture is near 45°, the raised groove portions appear higher in the picture. This results in perturbations in the audio signal. We don't have for the moment a solution, although the use of a glass pane alleviates this problem to some extent.

The case of warped records also may cause depth-of-field problems. Our approach here again consists in using a glass pane. This is usually applicable to bent discs, but not to severely warped records that cannot be kept flat under a glass pane.

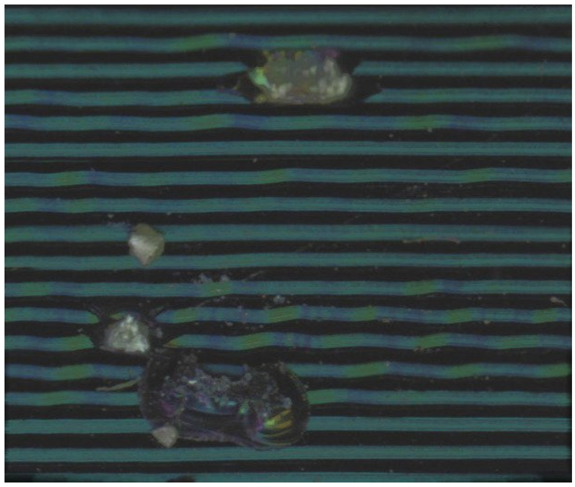

Figure 6: 7x5mm mosaic of pictures showing color-coded groove walls and blown blisters

4.3 Blisters, missing data

Zinc-based lacquer records stored in poor environments often exhibit on the core sprouts of oxide, that push up – and often break through – he lacquer surface, generating blisters or blown blisters. Even when not cracked, records affected by this condition become unplayable physically. Optical reading allows recovering the rest of the audio data. When cracks are thin or absent the routing problem is often simple enough to solve, and it becomes relatively straightforward to recover a complete playback of the record. The routing solver identifies the jumps across voids that have to be made, and the corresponding missing samples are flagged as such. A restoration tool can then be applied to re-generate the missing samples.

4.4 Masters and molds

Nickel-plated copper masters are often shiny enough to be played back optically using INA-Saphir. Male and female masters can be read without problem (the male masters are read after flipping the pictures and the reading order). Plastic and silicone molds can be read as well. But the resulting quality very much depends on the shininess of the master. From approaching conventional playback quality, it may come out much poorer when the master surface has become dull.

4.5 Sonorines, and other phonocards

Among the fascinating original recordings we were requested to play, we had to consider the Sonorine postcards [11]. As a coated cardboard direct recording medium, Sonorine could be considered as a lacquer record – shaped as a postcard. The very

Figure 7: A Sonorine postcard, poorly recorded, with cutter too high

brief life of the Sonorine and its player-recorder PhonoPostal system only lasted for 3 years, in 1905-1907, and was a commercial failure. Still, a number of recorded Sonorine postcards exist, and we were requested to read some of them. The Sonorines were recorded vertically (hill-and-dale) on a white coating material on the back of the postcard. Centering and rotation was achieved through two pins and a frame. By tilting the pickup head nearly vertically, we were able to get relatively good color pictures of the recorded content, and could extract the audio signal, even from the one in Figure 7, poorly recorded, where the cutter was operating too high, with only the lower lobes being cut through the coating.
The other cases of phonocards and spoken letters we were submitted were rather lateral-cut. The thin lacquer was often cracking into contiguous small cups, and the resulting quality was generally poor.

4.6 Exudates and dust

From our experience, one of the worst enemies of optical playback of lacquer records is the level of exudates. Exudates are clusters of palmitic and stearic acid – resulting from the breakdown of castor oil used as a plasticizer in the lacquer – sprouting from the disc surface. The clusters are whitish and opaque, and limit very much the visibility of the groove wall. On records in otherwise good condition, wet cleaning using detergent is applicable. But when cracks make this approach too dangerous, a common practice consists in playing several times the record, recording the output of each pass, and editing the audio from the best pass(es). The first pass is usually poor, plowing trough the exudates, but making way for subsequent cleaner passes. For the case of optical playback, we have implemented software-only exudates management, with limited success [12]. When possible, optical playback requires moving

Figure 8: Top: stiff and soft roller brushes usable for robust cracked records. Center: using a hand-held soft rotary brush to eliminate exudates and dust from fragile discs. Bottom: the same 8x6mm area from same disc before and after brushing.

obstructions off the whole groove walls, as addressed in next section.

5 Cleaning grooved record discs before scanning

We experimented using castor oil to soften and move away the exudates from cracked records, as suggested by Bal [13], but omitting the wet cleaning step. Although the oily groove wall often becomes easier to read, the oily residues cannot be safely dissolved and rinsed off, and the remaining oil makes subsequent storage unpractical. We rather shifted our approach to dry-brushing. Our first approach for dry-brushing was using a micro-fiber glove; it is reasonably fast, and applicable to most broken records. It however tends to smear exudates within the groove rather than to brush them away. We have met numerous cases of cracked aluminum-

Figure 9: One zinc-based record, before and after brushing and replacing missing flakes (playback in progress).

based lacquer discs with exudation, requiring removing as much as possible of the exudates. To this end, we designed two full-width 5rps rotary brushes for robust enough records; the first one with stiff bristles to eject exudates away, the much softer second one to eliminate the leftovers from the groove wall (Figure 8, top). Groove tracking from optical scans and resulting audio quality improve significantly, with a clear improvement over software-only exudates management.

To address the case of de-laminating records, we rather use a hand-held soft 5rps rotary brush shown in Figure 8, center, exercising caution, when necessary brushing trough a centimeter-sized window cut from a piece of cardboard. The edges of the window keep the lacquer flakes in place. Detached lacquer flakes are brushed separately through the same window, and are gently replaced in position after brushing, using a paper clipping cut as an acute angle tip. An extreme example is shown in Figure 9. After careful re-positioning, the set is covered by a glass pane for protection and scanning.

Despite cleaning, the achieved groove wall condition is usually duller and grainier than from a shiny record. The resulting quality may vary widely and, even after intensive dry-brushing, lowest audio signals may stay buried below the noise.

6 Audio restoration as a post-processing step

When trying to recover the audio signal from a damaged disc side, we always attempt to stay as close as possible to the original. We don't apply any de-emphasis curve, and we usually set the missing samples to zero. Given the large frequency bandwidth of the system (0 to 20kHz at 78rpm), spikes are often massively present in the delivered audio files. When noise and clicks make listenning too uncomfortable, in addition to the raw .wav file, we additionally generate a crude audible version, applying one of several of the following processes:

- Spectrum-based fill-in of missing samples
- Spectrum-based fill-in of samples beyond some threshold
- Click and crackle reduction
- Noise reduction
- High-pass (e.g. 15 Hz)
- High frequencies attenuation

Figure 10: We did not attempt to play this record

Beyond the scope of this paper, depending on the intended use, applying more advanced audio restoration tools may be considered beneficial, provided that the raw file is kept as the reference master.

7 Records INA-Saphir cannot play

We have found very few samples that could not be played at all. The examples below give an insight into the types of degradation that really cannot be played:

- Records where more than half of each turn is missing, such as the one in Figure 10.
- A half-toned printed phonocard. A better tracking strategy may be able to get some signal, but conventional playback of such media should be preferred when possible.
- Severely warped records that cannot be kept flat on a significant part of their surface.

8 Extending the user base

Since it was first demonstrated to the archive community [9] and exploited in the framework of the SirDuke real-case trial [14], the INA-Saphir

Figure 11: The INA-Saphir scanner, version 2

scanner was nearly entirely re-designed (Figure 11). The general disposition is the same, but a number of improvements were added. The increased pickup head size reduces the parallax problems, and an optical color-scrambling light guide improves the uniformity of the light source. The light source power was increased, improving the pictures Signal-to-Noise Ratio (SNR). The new DFM 22BUC03-ML camera board uses USB-2, and an IEEE-1394 FireWire card is not necessary any more.
The scanner is stabilized. It only requires AC power supply and 2 USB connections, can be operated on any sturdy stand, and can now be replicated and made available to audio archives and service providers.

The software is still evolving. Improvements are still expected in terms of:
• better groove tracking and decoding
• easier and faster identification of missing constraints and cuts when searching for best path
• user experience
We intend to improve the software by exploiting feedback from an extended user community. We are now in the position of delivering the scanner, still giving the users access to all future improvements to the software, released as open source.

9 Conclusions

We have tried to share our experience in optically extracting the audio signals from very damaged grooved disc records. We show that even de-laminating lacquer records can benefit from dry-brushing cleaning. Peeling-off lacquer flakes can be maintained in position using a window cut from cardboard, and accidentally detached flakes can be re-positioned before scanning. Some of such processes should be applicable to other optical and mechanical playback methods.

Although the software for decoding the scans is still being improved, the range of grooved discs that can be processed using the INA-Saphir system is already wide, including lateral and vertical-cut, broken, cracked, and de-laminated records with missing parts, regardless of the color or transparency, thickness… The main condition for extracting audio signal is that more than half of the recorded area is still present.

The INA-Saphir hardware is now stabilized and can be made available to archives and service providers for scanning endangered and fragile records.

Acknowledgments, disclaimers

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Neither large language models (LLMs) or image generative models obtained using machine-learning were exploited for producing this document. Except where mentioned, all records pictured in this paper were fully read optically.

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