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Saphir: Digitizing broken and cracked or delaminated lacquer 78 rpm records using a desktop optical scanner

Special focus on cracked lacquer discs

Presented on October 4th 2019, IASA 50th conference & 10th Joint Technical Symposium, Hilversum

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Summary

We present an optical alternative for recovering the audio signal from analogue audio disc records that cannot be read mechanically. The new desktop-sized Saphir system uses simple components and allows scanning optically a 78rpm disc side in less than 30 minutes, still keeping a good signal-to-noise ratio over all the frequency range thanks to reflective principles. The process is far from real-time, but allows recovering the audio contents of even very much damaged records, that may otherwise be lost forever.

Introduction

Conventional playback of 78rpm audio disc records is usually the preferred method for digitizing the records. It does require skills but is relatively fast and usually delivers good quality. But as far as broken discs and cracked or delaminated lacquer records are concerned, conventional playback is not an option, because the groove cannot be tracked reliably, and the risk of destroying the record or the equipment becomes unacceptable. Optical playback of those records was contemplated for a long time. Starting as early as 1929 [Brock-Nannestad 2001], designs were imagined, patents were applied for, and a number of prototypes were built. One design, the ELP system [ELP 1998] [Gaw 2004], achieved some commercial success, but it is not applicable to damaged records. The Saphir system is one of the very few processes that are currently applicable to records in critical condition.

Background and State of the Art

The first analogue audio discs were recorded as early as 1887, and distributed as commercial products by Emile Berliner in 1890 [Wile 1990]. Since then, the production has never really stopped, and the underlying technology has stayed very much the same: a horizontal disc rotating at a (usually constant) speed is engraved using a cutter (the cutter is sometimes replaced by a hard stylus that marks the disc surface). The cutter slowly moves from rim to center or from center to rim of the spinning disc, and additional audible high frequency motion is superimposed, depending on the audio signal to be recorded. The combination of those motions results in a spiral groove running on the surface of the disc. Reading such a record requires extracting the detailed shape of the groove. It can be done mechanically, using a stylus with appropriate shape, or using non-contact techniques

such as optical. We have tried in [Chenot 2018] to document as many as possible of the optical processes applied to reading analogue audio discs. We will only make a summary here.

The approaches may be classified in three main categories:

- *A-Reflective* method: Exploiting the reflective/scattering properties of the groove walls to infer the orientation of the groove walls
- *B-Imaging* method: Tracking the position of the groove walls using imaging tools
- *C-Interferometry* method: Using interferometry to measure the distance to the groove walls

Among the processes currently in exploitation, the ELP system [Stoddard 1986] [ELP 1998] [Gaw 2004] exploits the *A-Reflective method*, the Irene process [Fadeyev 2003] [Irene 2014a] [Irene 2014b] and the VisualAudio process [Cavaglieri 2001] [Stotzer 2004] [Stotzer 2006] [Johnsen 2008] exploit the *B-Imaging method*, as well as number of other processes used among others by [Feaster 2012] and [Levin 2019], exploiting flatbed scanners to generate their images.

Operating Principle

Our Saphir process uses the *A-Reflective method*, by casting, onto a small area ($2 \times 3 \text{mm}^2$) of the disc surface, a wide ($140^\circ \times 15^\circ$) light beam from a condenser, where the colour of the rays continuously depends on the illumination angle. The groove walls reflect those colours according to the law of reflection (reflection and incident angles are equal). As a consequence, from a remote viewpoint, the groove walls appear as coloured, and the colour is a function of the groove wall orientation, as shown in [Figure 3]. One of the advantages of this approach, compared to the *B-Imaging* and *C-Interferometry* methods, is that it can measure with good accuracy even minute details in the orientation of the groove walls, without requiring a costly high-resolution apparatus. Those details correspond to the high end of the audio spectrum. Our system therefore shares with the ELP system a fair behaviour in the highest frequencies, up to 20kHz. Our disc scanning process consists in acquiring a relatively large number ($\sim 60,000$) of overlapping $2.6 \times 2 \text{mm}$ $4 \mu\text{m}$ resolution pictures. Those pictures are analysed at a later processing stage. In favourable condition (shiny records), the process is fast and delivers fair quality signal. When the reflective properties are worse, or when exudates are present, we can use an alternative, slower method for extracting the slopes of the groove tracks, in that later case our approach becomes similar to the *B-Imaging* processes.

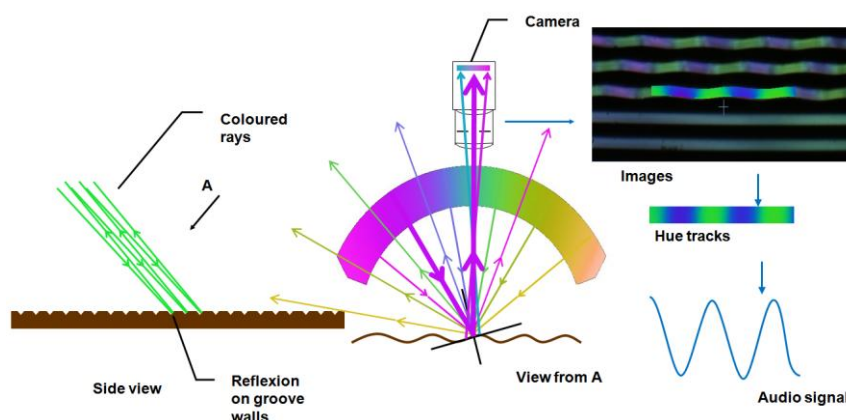


Figure 1: Principle of reading the groove walls angle through structured colour illumination

The New Saphir Scanner

Our initial design, described in [Laborelli 2007a] [Laborelli 2007b] [Laborelli 2007c] [Laborelli 2010] [Chenot 2018], was very slow, 3 hours per standard-sized disc, due to thermal constraints on the Ostar 1000 Lumen LE-UW-E3B LED light source, delivering six flashes per second. A new design over-driving the more powerful and energy-efficient 3x3mm Luminus PhlatLight CBT-90-W LED, has allowed us to increase the scanning rate to 46 frames per second, and to reduce the acquisition time of a standard record to a more tractable 30 minutes.

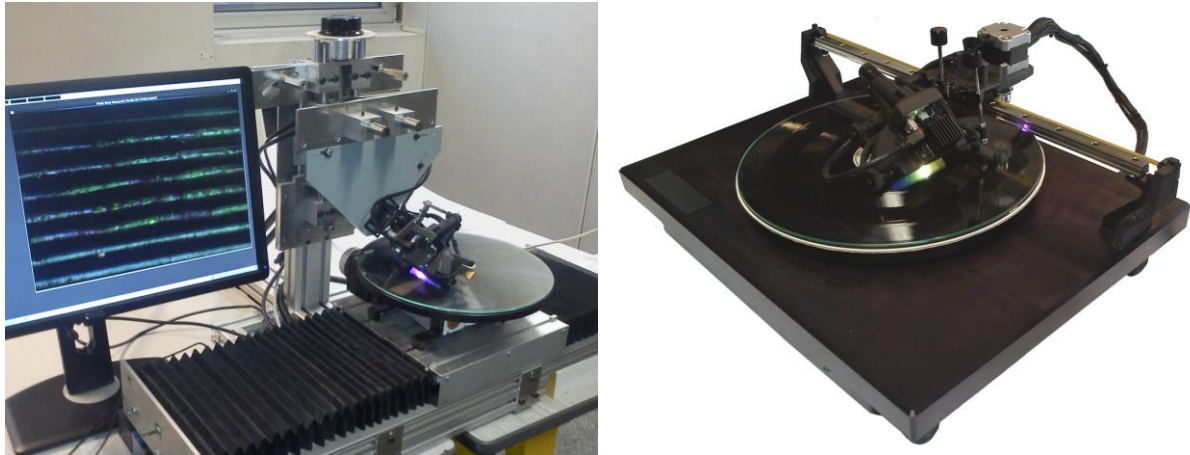


Figure 2 : The original prototype, left, and the new mobile scanner unit, right

The original bulky mechanism was simplified, the new scanner, completed end of 2018, has the same dimensions as a conventional turntable. Most of the components are of-the-shelf, or 3D-printed. The coloured filter is printed on a Kodak DS 8650PS film printer. The 1:1 140°×15° light condenser consists of two total internal reflection optical sector blocks lathe-turned from PMMA (a.k.a. Acrylite™, Altuglas™, Plexiglas™...) and polished. A simple flashed power driver for the LED is soldered on an add-on printed circuit board, plugged into a standard Arduino-based 3D printer driver. The scanner is driven by a standard Linux tower PC.

After scanning, the obtained pictures are software-processed, under the control of the operator. Our graphical user interface [Figure] allows to view the pictures, how they are analysed, and to adjust the parameters until the pictures and extracted signals appear as correct. This requires some 10 minutes effort, after which the software can run unattended in the background, allowing for other scans or other operations. The unsupervised processing time for an average record is typically one hour. It can be higher if the disc condition requires an alternative, slower, process. It can be lower if the same preset of parameters can be applied to a series of similar discs.

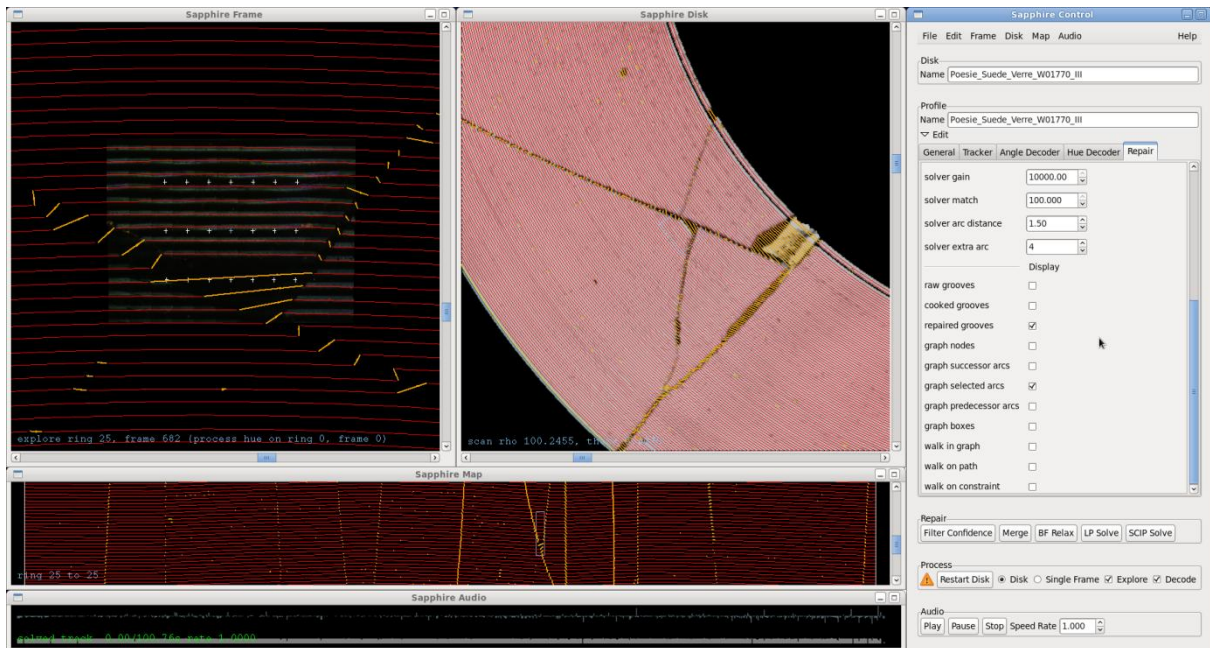


Figure 3: The decoding interface, highlighting the solved reconstructed path. Note the jumps over missing parts (top left and center views).

At the end of the processing, operations are necessary to ensure the re-connection of the obtained tracks in the correct order. We use the SCIP mixed integer programme problem solver [Achterberg 2009], [Gamrath 2016]: provided with the right set of variables and constraints, this tool can efficiently solve the complex problem of deciding how to reconnect groove fragments in the correct order, in a single path from the outer fragment to the inner fragment, using as many as possible of the fragments, still minimising the cost of the connections (jumps). On records where cracks are small or clearly visible, this operation can take a few seconds. In complex cases, this can become quite demanding to the operator, who has to identify the tracking errors, the missed cracks, and guide the process where necessary. The graphical user interface is essential for this process, where the user gives directives under the form of areas for cutting fragments, directing the connections, or direct forced links. The solver can be called iteratively until a satisfying solution is found.

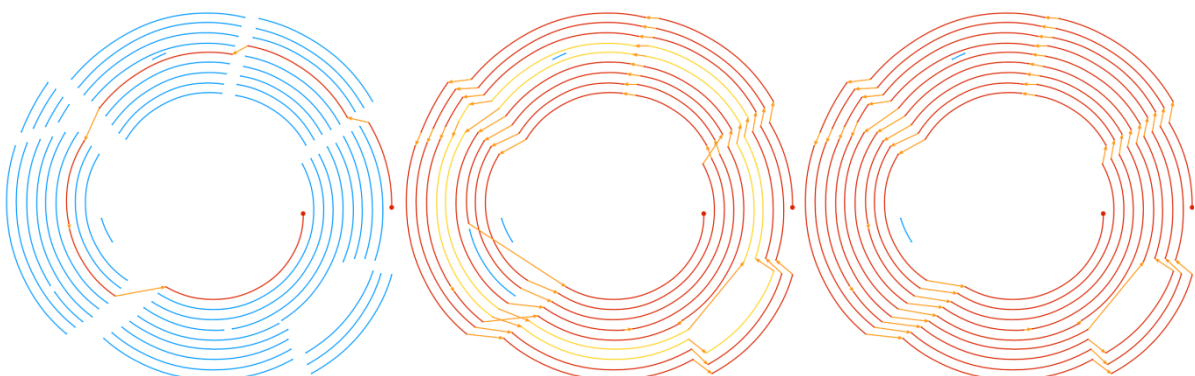


Figure 4: Potential solutions for the best-path reconstruction problem (synthetic example). Left: an acceptable but too short (low reward) path. Center: without non-crossing constraints, a high-reward but unacceptable path (self-intersections and cycles). Right: adding the non-crossing constraints makes the problem easier and faster to solve, the best path is found.

Overall, in simple cases, the complete decoding can be run in less than hour, with only 10 minutes of operator's time. In complex cases, the time budget can be increased to several hours of processing and of operator time. This is not satisfying, but a number of improvement tracks are being explored, we expect to drive the efforts down again.

Range of Operation

This project was initially developed with the objective of being able of playing unique direct-recording discs (lacquer discs) with a better quality and lower stress to the record than using the conventional approach. In terms of stress to the record, we are confident that the objective is achieved; not only the scanning head never touches the record, but we have found out that we could scan through a 3mm glass plate with equivalent results. The glass plate protects the record, and helps flattening the record and the potentially lifted lacquer flakes during the scan. In terms of quality, we do have a fair score in terms of frequency response, even at 33rpm, and we can jump over small obstructions on the disc surface. But a number of issues still arise: linearity is poor, the picture frequency may become audible, and the noise level increases with surface scattering, obstructions, and exudates. Despite our efforts, we only in very rare cases were able to reach quality levels comparable to conventional playback.

As a consequence, we have shifted our efforts towards recovering the signals from records that cannot be read by conventional methods. The first such condition occurs when the disc is broken, or when the lacquer on which the signal is recorded breaks into patches. Following the groove fragments in the correct order becomes quickly impossible, and the risk of damaging the stylus or the record increases considerably. Scanning optically eliminates this risk, and provides an opportunity to reconstruct the correct order after scanning. Our approach for reconstructing the correct path has evolved with experience. We now have a stable process where the operator and the solver complete each other's effort, allowing for identifying the correct path in minutes in the easiest cases. When lacquer flakes start to peel off, with lifted borders, the problem becomes more complicated, but putting the flakes back to approximately correct position, and keeping them flat under the glass plate still allows for scanning and extracting the signal. This approach allowed us to recover records contents that were already considered as irrecoverable. When a lacquer flake or a disc chunk is missing, nothing is lost: we can let the solver find the best way of jumping over the missing pieces, and have ways of adding silence or propagating the adjacent signals into the missing sections, provided that the missing parts are shorter than 0.1 second.

We were surprised to find that it was still possible to adjust the gain of the 3 colour channels to obtain audio signals from coloured records or dis-coloured records. This applies to a number of lacquer and gelatine disc brands, including Pyral and Thorens, where lacquer ageing results in the lacquer turning into a greenish or yellowish transparent material. The quality obtained is sometimes surprisingly good, given the apparent state of the record.

Matrices and stampers are molds that were used to duplicate records, usually for mass-production. Their surface is usually highly reflective, which allows obtaining a fair quality, without having to prepare a print from the stamper. Provided the correct rotation direction is taken into account, our process can extract the contents of such molds.

A number of amateur formats allowed recording on aluminium discs personal contents or radio broadcasts. Those systems often used an embossing tool for recording onto the bare aluminum surface. The colour scheme for reading such records does not work as well here as the slower slope-tracking process.

Our approach is designed for monophonic lateral modulation disc records. This should eliminate from the applicable range all hill-and-dale records. But in practice we have found that, by adjusting the orientation of the scanning head, we could obtain audible but distorted audio from such records, giving hope for broken sapphire records. We have also worked on a number of 1905-1907 hill-and-dale Sonorine postcards collected by Tom Levin [Levin 2017], and found that we could play them relatively easily. The set of pictures on next page gives a good example of records that were successfully recovered using our system.

Small gaps between groove fragments are eliminated by direct stitching. But on the examples above, large gaps can sometimes be seen. Beyond standard-size crack gaps, the audio signal is replaced by silence for the duration of the gap. This usually makes the audio hard to the ear. We therefore also produce an alternative version of the audio file where gaps up to 0.1 second can be replaced by extrapolated content.

Bring Your Own Disc !

We are still in the process of assessing the range of disc records that can be read using our Saphir process. In that perspective, all attendees to the 2019 IASA and JTS conferences in Hilversum were invited to bring their records and come to us in the exhibition area of the conferences in Hilversum (NL) from September 30th to October 4th. Over 4.5 days, we were able to scan 36 sides from 21 different records. We delivered to the participants, on-site or later, the audio signals extracted from those records:

- 3 broken glass-based lacquer records, with missing parts.
- 10 black aluminum-based lacquer records, cracked or delaminated, some of them with missing flakes and/or dis-coloured.
- 1 yellow cardboard-based record "spoken letter".
- 5 "shellac" records, dated from 1920 to 1940, broken, or destroyed from multiple playbacks.
- 1 "Pliaphon" embossed aluminium record.
- 1 "Berliner" zinc master from 1890-95

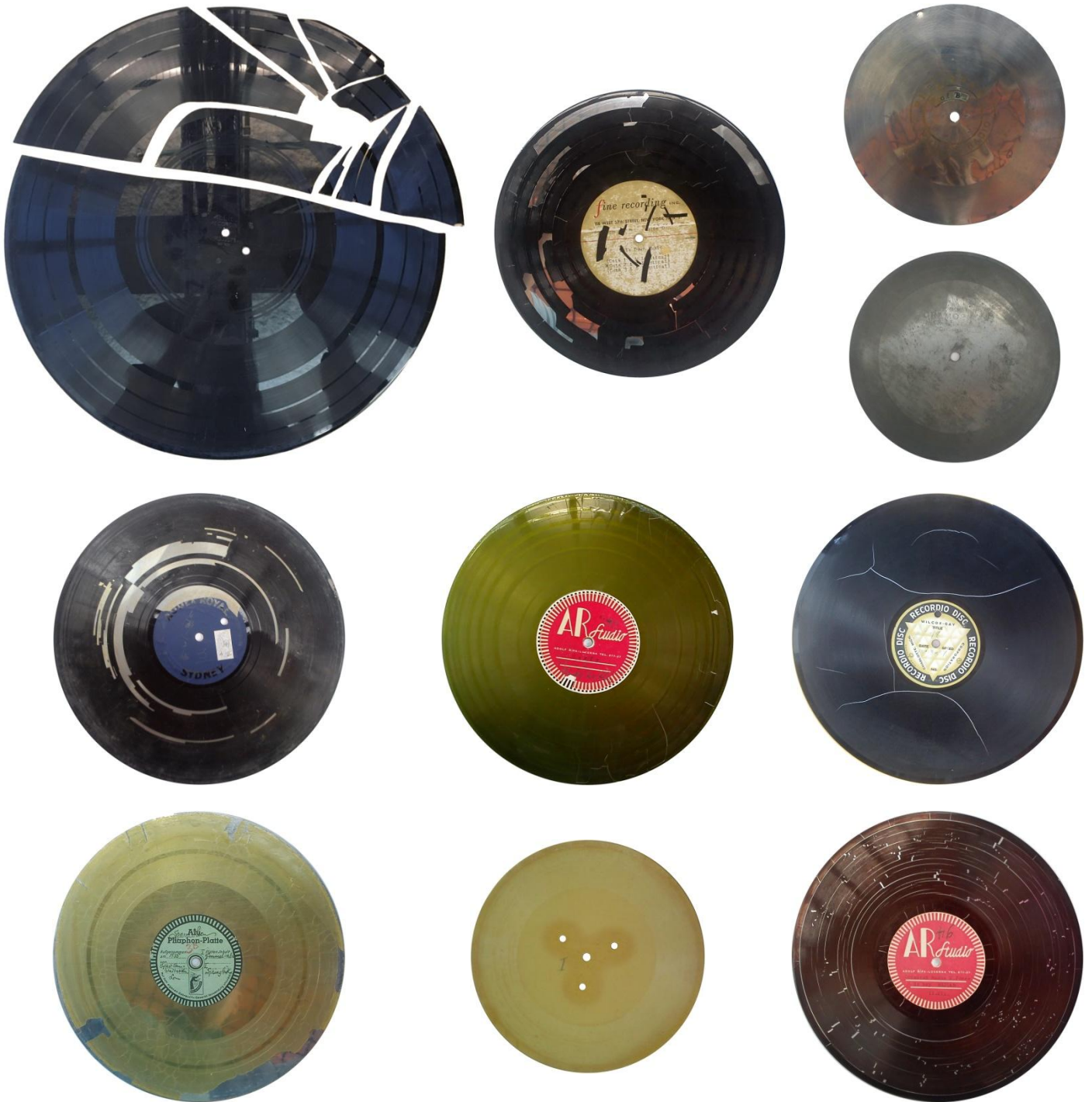


Figure 5: some of the records that were successfully recovered using Saphir during the conference.

Conclusion and Future Work

The new Saphir scanner is transportable and allows scanning a standard-sized recorded disc in 30 minutes. The decoding process takes a little longer, but offers the possibility of testing the best configuration, without further damage to the record, until the audio is delivered. This process can be applied, with no risk to the record on a wide range of analogue audio discs. We are now working on improving speed on the slowest tasks within the decoding stages, and on replicating the new scanner

at affordable cost. We expect to be able to deliver new units, first to exploitation services within INA, and then to other audio archives and service providers, providing them an affordable way of recovering those records that cannot be played using conventional means.

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