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Hochschule für Technik und Architektur Freiburg

Bachelor Thesis

2D and 3D Scanning of Metallic Records and Masters

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Abstract

The Harvard University possesses a collection of about 3000 aluminum discs that were recorded by Milman Parry in the early 1930s. These recordings were made during trips to Yugoslavia, where story-tellers had been recorded for linguistic studies. Since a common playback by stylus may damage these unique discs, a way of digitization without physical contact is searched. A possible solution is the existing disc scanning in 3D that works well for other disc types. In order to estimate the capabilities of the 3D scanning for aluminum discs, this project aims to introduce this special disc type into the existing technique. Therefore, the acquisition of the disc data has been adapted for the very shiny aluminum discs and a specific algorithm has been developed that processes the small and particularly formed grooves. The results have shown that these adaptations allow reconstructing audio of reasonable quality from the aluminum discs and that the 3D scanning is a promising way of digitizing the aluminum disc of the Milman Parry collection in a contactless way.

Acknowledgments

A special thank goes to my professors Ottar Johnsen and Frédéric Bapst who made this exceptional project at the Lawrence Berkeley National Laboratory possible at the first place. Furthermore, I want to thank Earl Cornell who entered into constructive discussions and helpfully answered any questions I had concerning the 3D system and the program code. Another special thank goes to Carl Haber for giving me the opportunity to work in his team and for the inputs and ideas he brought in. At last I want to thank Christiane Jeckelmann for the rewriting and the corrections she did.

Content

1 Definitions of terms

In order to avoid any confusion, this chapter aims to explain and visualize terms used in this document, which are connected to the world of disc records.

Groove

The groove is the carrier of the sound information on a disc. It is a kind of trace, which is either cut or embossed into the disc during the recording. The needle follows this trace in order to play back the sound.

Figure 1: Typical shape of cut groove

Groove center

The groove center is the middle of the groove. By determining its exact position, the precise position of the needle is known. This knowledge is used to reconstruct the sound digitally.

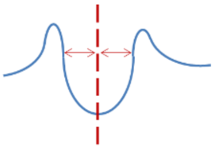

Figure 2: Groove center

Groove side/bottom

The groove side is meant to be one of the two sloped parts of the groove. The bottom is the flat or almost flat part between the groove sides.

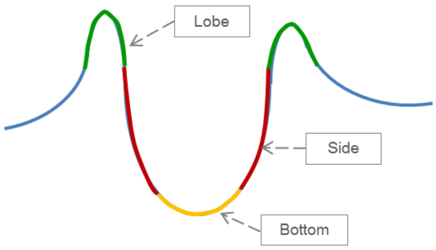

Figure 3: Groove sections

Groove lobe

The groove lobe is a region of the groove side that surmounts the groove top. The lobe is only present if the groove has been embossed instead of cut. It corresponds to the pushed material during the embossing.

Groove top

The usually flat part between two grooves is called groove top.

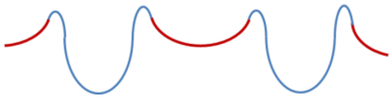

Figure 4: Groove top

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2 Introduction

A long time ago, in 1860, a certain Édouard-Léon Scott de Martinville performed the first known sound recording in human history: he recorded himself singing the song “Au clair de la lune”. Although his device, the phonautograph, could not play back the recording by that time, this was the beginning of a long evolution. It was then Thomas Edison who invented the phonograph cylinder and therewith allowing the first playback of recorded sounds. This device later led to the invention of the disc phonograph, whose further developed vinyl type is still used today. Likewise, other recording types as the magnetic tape or the compact disc, contributed to the evolution. With the development of the personal computer, Internet and the portable mp3-players, the manner of sound recording and play-back changed significantly in the last few decades. Through these inventions, physical sound carriers are no longer required nowadays; sound has become a sequence of bits, transferable and playable everywhere on every device. [1]

Through the evolution of the sound recording and the related development of always newer and better devices, the old techniques and devices have been replaced. In the first few years this was not a problem, but the longer a technique is out-of-date, the more difficult it gets to find a device enabling the play back of the recordings. Another point is the aging of the recordings and the fact that their playback is based on physical contact leading to abrasion; a particular problem for unique recordings. Damage on these recordings is tantamount to loss of information or knowledge of earlier times.

In times of digitization, there is an intention of digitizing these old and sometimes unique recordings in order to preserve them for the future. A solution of doing this for mechanical carriers without physical contact is given by the optical technique.

Knowing the demand and the utility of this technique, a team around Carl Haber has specialized in optical scanning and reproduction of mechanical recordings at the Lawrence Berkeley National Laboratory (LBNL). They started in 2003 by scanning early shellac discs, and over the years the system has been extended for further discs types and other mechanical recordings. At the beginning, the reflection of the carrier’s material was used for the scanning in order to get a two dimensional replica, which then could be processed. For supports with less response on the two dimensional system, a three dimensional system was developed later.

Through the years, these two techniques have always been improved and the amount of readable devices has increased. At the same time the project became more and more known, so that today people from far away bring their unique or special recordings. Depending on the construction and the structure of these brought recordings, the system first has to be modified so that they can be reconstructed. Thus, development continues, especially since there are a lot of ancient, unique and special recordings that are part of the human history or otherwise important to be preserved for the future.

2.1 Context

Lately, the University of Harvard contacted the audio laboratory at LBNL with the idea of digitizing the disc collection of Milman Parry that is stored in their archives. This collection is unique because it is formed of about 3000 unique aluminum discs that were recorded between 1933 and 1935 in Yugoslavia and contain recordings of local story-tellers. Milman Parry did these recordings in order to study the oral poetry. [2]

The aluminum discs of this collection have specific characteristics that make their scanning and processing very difficult in comparison to other, more known, disc types:

- Due to the material the discs are very shiny.
- The groove depth is very small.
- Since the groove is embossed and not cut into the disc, the groove contains lobes that form buckles into the flat top of the disc.

Knowing these characteristics, this diploma work aims to find a solution to scan and process the aluminum disc of the Milman Parry collection. In order to do so, about 25 samples of the over 3000 discs are brought from the archives to LBNL. These 25 discs are chosen in different time steps, so that the evolution and the differences in the collection can be included in the development.

Since the 3-dimensional technique can give more information about a disc and previous investigations have shown some difficulties scanning the aluminum disc in 2D, the project basically focusses on a solution with the 3D system. The 2D is mainly taken into account as a reference and for comparison. However, this can change, in the case that during the project the 2D technique is found to be more appropriate.

2.2 Objectives

The aim of the project is to find a way to reconstruct the aluminum disc of the Milman Parry collection by using existing optical techniques. Due to the special characteristics of this disc type, both adaptations on the existing system as well as new algorithms have to be found and developed. In order to achieve this task, the project is subdivided into the following objectives:

- Adapt the initial 3D scanning mechanism for the aluminum recordings, so that the characteristics of this disk type can be compared, analyzed and processed.
- Define the most appropriate parameters for the scanning of the aluminum disks.
- Analyze and document the groove structure of the about twenty available disks out of the Milman Parry collection in order to get an overview of the groove characteristics and quality of the recordings in that collection.
- Do an analysis of the different groove measurement algorithms and compare them so as to determine the most appropriate ones.

- Develop a filtering code in order to reduce or remove wrong values from the data and as a consequence improve the reconstruction of the recording.
- Evaluate the achieved results at the end by comparing the signal, noise and error rates.

2.3 Documentation structure

This document is divided into four main parts, whereas each part can contain more than one chapter. To introduce the systems that are used and adapted for the aluminum discs, the first part introduces the scanning techniques with its corresponding hard- and software. The second part then focuses on the aluminum discs; their history, their characteristics and how they can be scanned. The third part presents the developed algorithm that allows processing the aluminum disc before finally the last part evaluates the project by presenting the tests and results as well as the encountered problems and possible further developments.

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3 Scanning techniques

For several years now, the audio laboratory at the Lawrence Berkeley National Laboratory is equipped with a 2 dimensional camera as well as a 3 dimensional camera. Although it is a fact that the 3D camera acquires more information, it does not always achieve better results; both techniques have their advantages and disadvantages. In order to understand the differences and similarities of the two systems, this chapter aims to presents them in a more detailed way.

3.1 Hardware

Although the 2D and 3D scanning techniques differ a lot, they use the same hardware. One exception is the cameras, which have to be different because one of them acquires one dimension more than the other. Putting the cameras aside, the used construction is composed of the following components:

- Metal composition
- Keyence measurement laser
- Newport XPS controller
- 3 motors
- Turntable

The self-developed metal construction thereby serves as a fixture for the Keyence laser and the camera that have to operate from the top of the turntable. Therefore the discs are placed horizontally.

The three motors basically allow all movements that are needed for the scan. Two of them are connected to the turntable where they are responsible for the movement to the disc center, called x-shift, and the rotation. The third motor is attached to the camera and allows adapting the camera height. This movement is called z-shift and is necessary for the focusing. Figure 5 shows the 3 motors and their emplacement on the composition.

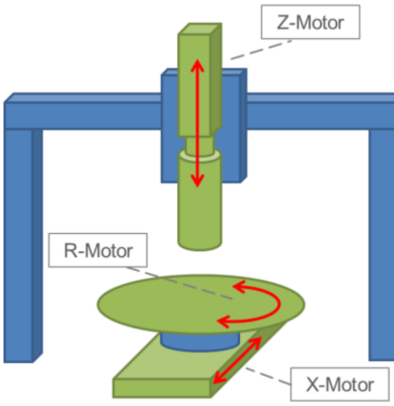

Figure 5: The 3 motors of the scanning systems

All three motors as well as the laser and the camera are connected to the XPS controller that enables their control. Included in this control is the provision of the acquired data so that they can be collected and further processed by a computer. Thanks to a special library, LabVIEW can control the XPS controller and the attached devices.

The laser is used to measure the effective height of the disc, which allows adapting the z-shift motor according to the disc height. Through this procedure, height changes on the disc can be predicted and thus compensated so that the camera always remains in focus.

Furthermore, the entire construction places on a special table that intercepts any fast changes of the floor.

3.2 2-dimensional scan

The 2D scanning technique was the initially developed system at the audio laboratory at LBL. In the two steps presented by the following subchapters, an audio file of the scanned disc is obtained without any mechanical contact.

3.2.1 Data acquisition

The first step towards the audio file is the data acquisition, which basically involves the control of the motors and the storage of the acquired data. The system that manages this part is called IRENE and mainly links the hardware and the software.

Measurement

The 2D principle uses the reflectivity of the discs to digitize the groove movement and by that the sound information. Therefore, the light of a light source is guided on the disc and the camera captures the intensity of the reflected light. As a result, each capture is defined by a line of 3.072mm with 4096 measured intensity values. In order to cover the largest possible surface during the scan, this light line is adjusted orthogonal to the groove direction.

It is also possible to perform side lighting instead of top lighting, which changes the resulting picture as neither the flat parts of the discs nor the groove bottom are reflected, but instead only a part of the groove side gets reflected. Since the groove side also contains the sound information, this data can be processed the same way as the top lighting data. Depending on the disc characteristics, the result with side lighting is even better than with top lighting.

Image size & Sampling frequency

By rotating the disc, a series of captures form an image with a width that is determined by the line width and a height that is given by the number of samples taken. Thereby, the image size is given as follows:

$$size_{image} = n_{points} \cdot n_{sample} = 4096 \frac{points}{sample} \cdot 80000 \frac{sample}{revolution} = 327.68 \cdot 10^6 \, points \qquad (3\text{-}1)$$

n_{points} : $number\ of\ points\ per\ line$
n_{sample} : $number\ of\ samples\ per\ revolution$

Since a sample line of 4096 points covers 3.072mm, the 327.68 10^6 points of a revolution cover a ring of 3.072mm of the disc.

The given number of samples per revolution furthermore allows determining the sampling frequency used for the 2D system. Therefore, the sampling duration is calculated first.

$$T_s = \frac{t_{rev}}{n_{sample}} = \frac{\frac{1}{\omega}}{n_{sample}} \cdot \frac{\frac{1}{78\,rpm \cdot \frac{1\,min}{60\,sec}} \cdot}{80000\,samples} = 9.62\mu s \qquad (3\text{-}2)$$

$$f_s = \frac{1}{T_s} = \frac{1}{9.62\mu s} = 104kHz \qquad (3\text{-}3)$$

T_s : $sampling\ duration$
t_{rev} : $duration\ of\ one\ revolution$
ω : $angular\ velocity$
f_s : $sampling\ frequency$

Storage

Instead of generating one picture per rotation or for the entire disc, the IRENE system creates nine pictures for one revolution. The last picture, however, exceeds the 360° of one turn. It is used to move the turntable into the next position while turning. Because of this additional picture for the x-motor movement a ninth of the acquired data is worthless. On the opposite, this technique allows scanning a disc without any interruption from the beginning to the end.

Figure 6 shows the scanning principle with the nine generated images (A_1 to I_1) for one revolution.

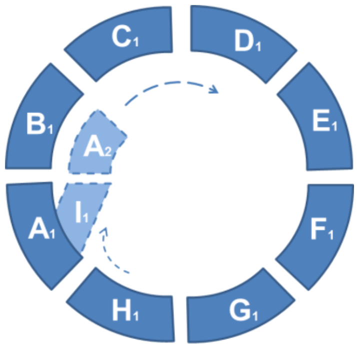

Figure 6: Generated images with 2D scan

The entire acquisition can be controlled by one LabVIEW program that is easy to use due its simple user interface with good explanations.

3.2.2 Data processing

After the acquiring part, the eight images per revolution of the disc are stored at the chosen place on the computer and are ready for processing. This part is executed by the RENE program; a software explicitly developed for the processing of 2D scans which basically allows extracting the sound from the stored gray-level images by applying an edge detection. This is made possible by the fact that the reflected groove bottom is white and the non-reflected groove sides are dark gray or black. Figure 7 shows a typical result of the 2D scan, where the groove bottoms can be easily seen in the black stripes of the groove sides.

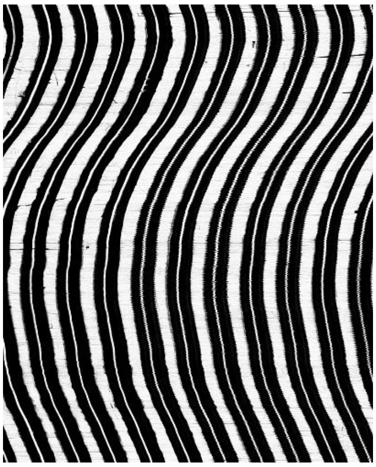

Figure 7: Typical image of a 2D scan

As the images can differ a lot depending on different disc types or different recording qualities, plenty of parameters are provided in order to adapt the behavior of the edge detection. Furthermore, there are some implemented additional tools helping to find the source of an audio file of bad quality. Figure 8 presents the graphical user interface of the RENE by pointing out the three sections.

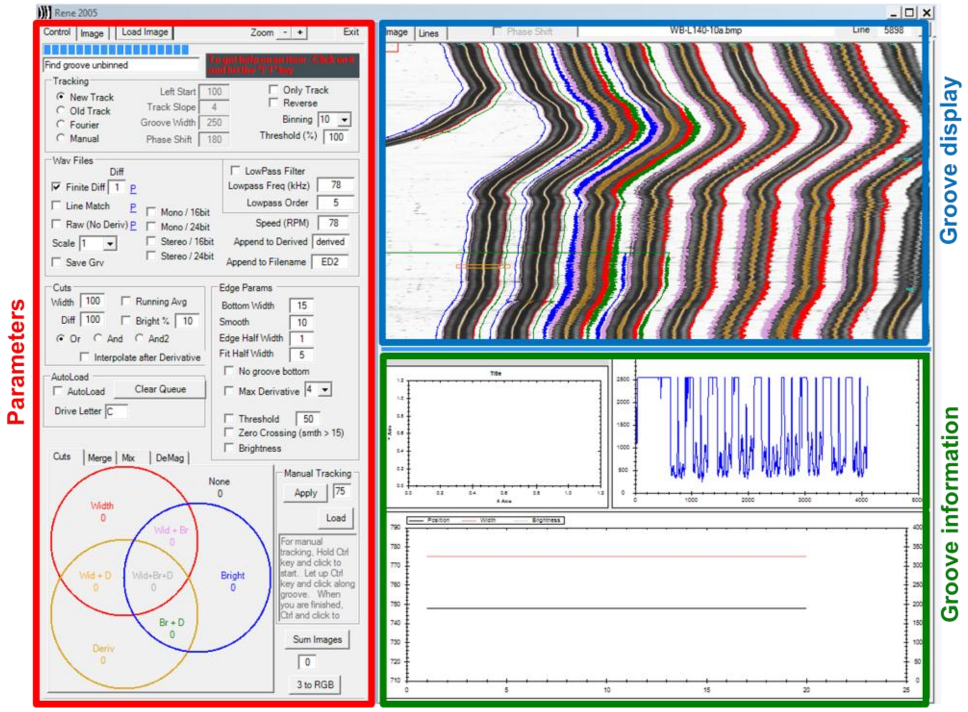

Figure 8: RENE program

3.3 3-dimensional Scan

The system of the 3-dimensional scan was introduced after the 2D system and has been very time consuming at the beginning because the depth was measured with only one point. By replacing the camera, this problem could be reduced, but the 3D scan still takes longer than the 2D scan. As in the 2D technique, the data acquisition and the data processing are performed in two steps in the 3D technique. These two steps are presented in the following subchapter and since the 3D technique seems to be the more promising one for the aluminum discs, the explanation for it will be more detailed.

3.3.1 Data acquisition

Even if the principle for the data acquisition remains the same for the 3D system than for the 2D system, there are some important differences implying that not the same acquisition software can be used.

Measurement

As the name implies, the 3D system allows getting a topological view of the disc surface. This depth information is obtained by using the chromatic aberration whereby a light is guided through a lens to the disc surface. Not all the wavelengths in the light are thereby broken with the same angle so that the foci of the different colors in the light spectrum are shifted in depth, as is shown in Figure 9. In order to determine the depth of the surface, the sensor then analyzes which wavelength of the reflected signal is in focus. In addition to the depth information, the camera also captures the intensity of the reflected light.

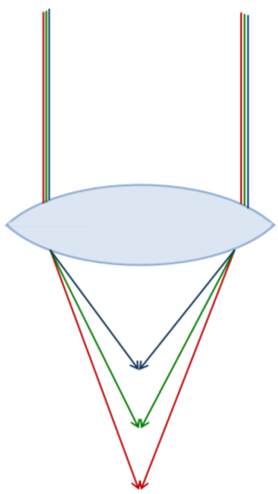

Figure 9: Different focals depending on the wavelength

Unlike the first 3D camera, the current camera can capture 180 points at the same time whereby each point contains its separate fiber. Similar to the 2D camera, the points are aligned linearly and the line is adjusted orthogonally to the groove of the disc.

Figure 10 shows an example of a captured line from a usual disc surface with the 3D technique.

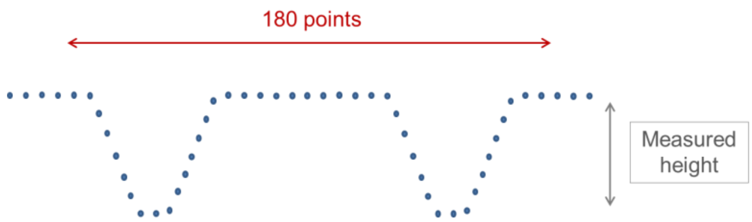

Figure 10: Example of groove capture

Disc tracking

Same as for the 2D, the height (z-position) has to be adapted during the scan in order to compensate height changes on the disc, which are for example due to vaulting. This so-called tracking is needed because the range in which the depth can be measured is only 350µm. In contrast to the 2D system that uses only the tracking by the help of the laser, the 3D system can track without laser. Essentially, the following tracking modes are available for the 3D scans:

- Laser
- MPLS
- Gathering

As explained earlier, the laser tracking uses the measured height from the laser to adapt the z-motor. Since the measurement point is slightly before the position where the capture of the camera is taken, the laser measurement slightly has to be delayed.

The MPLS tracking is independent of the laser. It uses the mean value of all the 180 measured depths per sample to calculate the needed height change of the z-motor. Due to the fact that the calculated output (z-change) directly affects the input (mean value), the MPLS tracking is a feedback system.

The third tracking technique is the gathering. This type was introduced for cases in which the same revolution is scanned multiple times. Due to the fact that the non-flatness of the disc is the same for each of the multiple scans, the same z-motor height correction can be used. Therefore, a first rotation is made in order to store the height information measured by the laser. All the following rotations then use this stored height information in order to adapt the z-motor. This tracking especially facilitates the merge of the multiple scans.

Image size & Sampling frequency

As for the 2D system, the image size of the scan is limited by the linear resolution of the camera. For the used 3D camera the distance between two points is 10µm, with the result that the range of the 180 points is 1.8mm. This resolution does not always meet the standard. Therefore, the multiple pass technique has been introduced. Each part of the disc is thereby scanned multiple times but always with a little shift. This way the distance between two points can be reduced by the factor of pass numbers. Figure 11 shows an example of a 2-pass compared to the usual 1-pass.

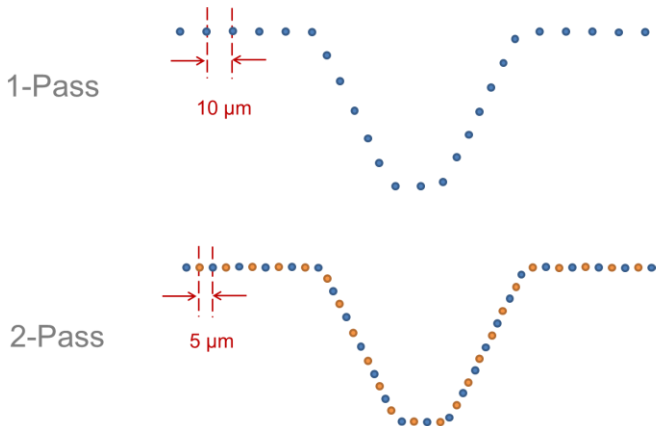

Figure 11: Comparison between 1-pass and 2-pass

Contrary to the width, the height resolution is not related to the number of passes but on the angle distance between two samples. As a result, the image size of one rotation is defined as follows:

$$size_{image} = 180\,\frac{points}{line}\cdot n_{pass}\cdot\frac{360°}{Dphi} \tag{3-4}$$

n_{pass} : $number\ of\ passes$
$Dphi$: $Angle\ between\ samples\ \left[\frac{deg}{sample}\right]$

Since the angle between two samples and the number of passes are parameter values, the image size is not fixed.

The sampling frequency is not predefined. The reason for this is again the changeable angle between two samples, which determines the number of samples per revolution. The following formula show on what the sampling frequency is depending.

$$T_s = \frac{t_{rev}}{n_{samples}} = \frac{\frac{1}{\omega}}{\frac{360°}{Dphi}} = \frac{\frac{1}{78\,rpm \cdot \frac{1\,min}{60\,sec}} \cdot}{\frac{360°}{Dphi}} = \frac{0.7692\,\frac{s}{rev}}{360°} \cdot dZ \tag{3-5}$$

$$f_s = \frac{1}{T_s} = \frac{360°}{0.7692\frac{s}{rev}} \cdot \frac{1}{Dphi} \tag{3-6}$$

T_s : *sampling duration*
t_{rev} : *duration of one revolution*
ω : *angular velocity*
f_s : *sampling frequency*

Storage

In contrast to the IRENE system, the 3D system stores only two files per disc; one for the depth information and one for the intensity information. This means that all revolutions and all multiple passes can only be determined by knowing the structure of the generated file, which is the same for both files. Another difference compared to the 2D system is that the date is not stored as an image file, but as a binary file with the endings .pri for the depth file and .bri for the intensity file.

A LabVIEW program allows doing the entire data acquirement. The use of this program however is more complicated than the 2D program. Reasons for that are the missing explanations and the larger amount of parameters due to the different tracking possibilities and the ability to scan other records than discs.

3.3.2 Data processing

The processing part of the 3D data is performed by software PRISM that has been developed in the audio laboratory at LBNL like the RENE program. Its behavior is shown by the flowchart in Figure 12.

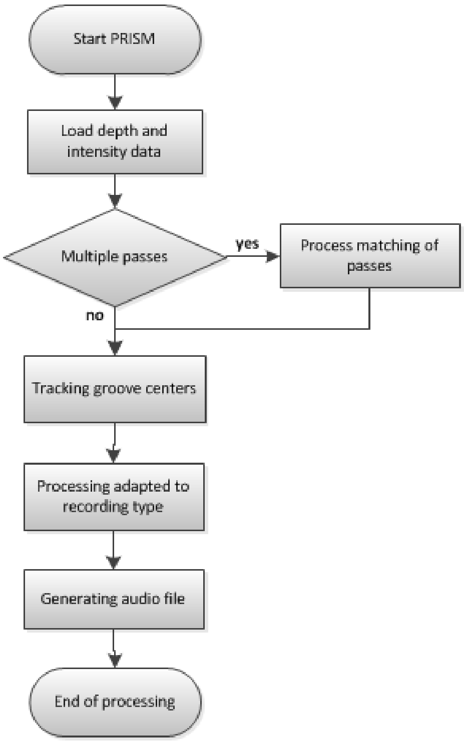

Figure 12: PRISM program procedure

In a first step this program loads the generated files into the memory. If multiple pass is used, the values of each pass are interleaved. Furthermore, the groove tracking is performed in order to get an idea of the searched groove center. This primary tracking is then used to apply the chosen processing type, which varies between the different disc and recording types. The aim of the processing algorithms is to find the exact groove center. By combining all the calculated groove centers at the end, the sound can be generated and stored in an audio file.

Similar to the RENE program, there is a huge amount of parameters in PRISM that allow adapting and modifying each steps of the program. Figure 13 shows the graphical user interface of the PRISM program by pointing out the four sections.

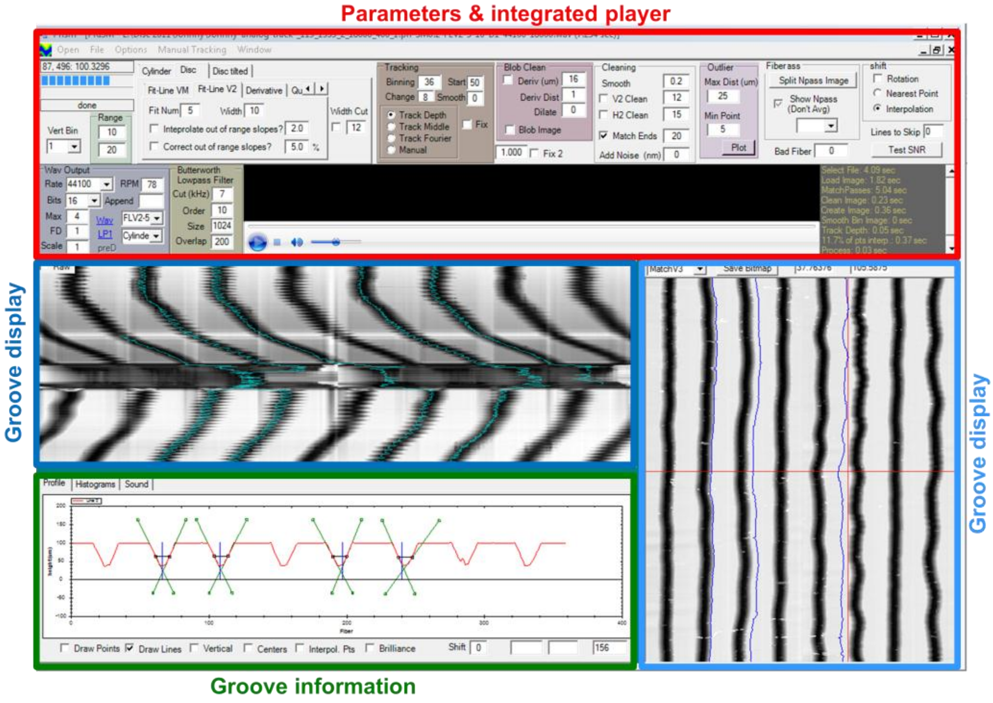

Figure 13: Prism program

4 Aluminum discs

The material Aluminum as a disc recording material was introduced in the late 1920s and used until the 1940s. At the beginning, the discs were entirely made of aluminum and served as on-time recording. Due to the characteristic of the aluminum and the fact that no other materials are involved, these discs are said to be very durable if they are stored and played carefully. Figure 16 shows an example of such an aluminum disc.

Figure 14: Aluminum disc of the Milman Parry collection

For the recording, however, the metallic characteristic of the aluminum entails some difficulties. Therefore, the groove is not cut or engraved into the disc, as this is typical, but embossed with a certain pressure using a blunt diamond. This leads to the special groove structure that is explained in chapter 4.2.3. Using aluminum discs demands also a particular playback. Since the aluminum is a metal that can be damaged by other metals, the usual steal needle cannot be used. Therefore, the fiber needles made from bamboo or plant thorn are used for aluminum discs. Although the bare aluminum discs are known to be durable, the World War II signified the end of a lot of them, because aluminum was a highly demanded good for the war industry. [3]

In the mid 1930s a new disc based on aluminum was developed. In contrast to the bare aluminum discs, these acetate discs contain a layer of lacquer onto the aluminum. This surface simplifies the recording as it allows cutting the groove instead of extruding it. Furthermore, these discs can be re-recorded by melting the lacquer and re-cutting a new groove on it. Compared to the bare aluminum discs the acetate discs achieve a better sound quality, but have a lower durability instead. [4]

Since the discs of the Milman Parry collection are all recorded on bare aluminum discs, the acetate discs are not described any further in this document. The following subchapters aim to present Milman Parry and the characteristic of the discs in its collection. At the same time, the scanning of these particular discs will be discussed.

4.1 Milman Parry

Milman Parry was born in 1902 in Oakland (CA, USA). He got his Bachelor and Master degree at the University of California in Berkely and went to Sorbonne (FR) to write his thesis, which was finished by the year of 1928. In his dissertation he analyzed the Homeric poetry and showed the use of different kinds of patterns that are used in oral poetry by the story-tellers in order to remember the details of stories.

Figure 15: Milman Parry[5]

At the time when he was an Associate Professor at Harvard University, he did two trips to Yugoslavia, where the story-telling was still well-established compared to other countries. In order to be able to study and preserve this oral poetry he recorded the stories on around 3000 aluminum discs. His work had been continued after his dead and today the disc are all part of the Milman Parry collection which is stored in the Widener Library at the Harvard University in Massachusetts [2]. Since the playback of the disc is difficult and will not get easier with the years, the library explores the possibility of digitizing the collection optically in order to preserve Milman Parry's work for the future. Therefore, the University sent 26 examples of the collection to the audio laboratory at LBNL for ability tests.

4.2 Characteristics

The recording and the material of the aluminum discs differ a lot from other industrial manufactured discs so that big differences can be found in their characteristics. This subchapter therefore aims to present an overview of the characteristics of the 26 provided aluminum disc.

4.2.1 Profile

The Milman Parry collection consists of about 3000 aluminum discs in many varieties. An explanation of this could be for example that the embossing tool might stump with the amount of recorded disc or that the difference results from the use of other recorders. In order to be able to analyze the differences between the discs, 26 sample discs of the Harvard University from different time periods are selected.

By analyzing the 26 discs and taking surface samples of each of them (result in file *B3DM_GrooveSamples.pdf*), following profile could be made. It is assumed to be valid for the entire collection.

Parameter	Value
Speed	*78rpm*
Size	*10" (25,4cm)* *and 7" (17,78cm)*
Groove gap	*~260µm*

Parameter	Min	Max	Median
Groove depth	*4µm*	*15µm*	*7*
Groove width	*50µm*	*110µm*	*80µm*

The speed of the discs is, as it was common during the 1930s, 78rpm and therefore not exceptional. The same applies to the disc size; both encountered sizes, 10" and 7", are standardized. It is however supposed that a minority of the collection is 7" because only one of the 26 discs has that size.

The profile also shows that there are big differences of the groove parameters between the discs. Nevertheless it has to be noted that this is mostly due to one disc which contains bigger and wider grooves. It could be that this mentioned disc is exceptional because it is not labeled with a number, as are the others.

Moreover, there could not be determined any dependence between the groove parameters and the period in which the discs were recorded. A possible reason might be the sharpening or replacement of the embossing tool from time to time or the use of different recorders.

4.2.2 Material

Aluminum is a soft metal and is therefore adequate for extruding whereas a certain pressure is needed in order to emboss a playable groove. This should be deep enough so that the needle does stays in the groove.

Although the material leads to restrictions in the play-back quality, it provides a good durability and is very solid. Contrary to the shellac disc, there is no risk of breaking an aluminum disc.

Another characteristic of the aluminum is its shininess. This is particular inconvenient since as well the 2D as the 3D scanning technique are based on light reflection. One might assume that a shiny surface is ideal to reflect light. This is true, but the problem is that the sloped groove sides and the other unflat parts are not perpendicular to the incoming light. In this case the shiny surface reacts like a mirror that reflects the light with the incoming angle. Almost no light is reflected in the direction of the light source, where the camera is placed. Figure 16 illustrates this by an example.

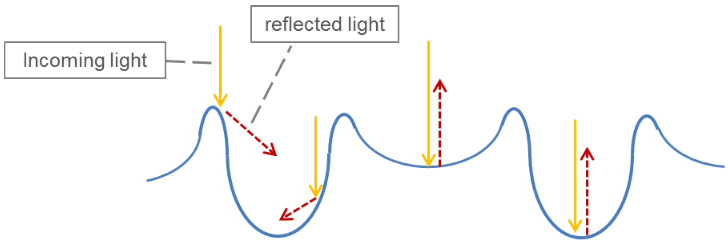

Figure 16: Mirror effect on aluminum discs

This reflection characteristic of the aluminum disc leads to a large range of captured intensity values. For the flat parts perpendicular to the light source, the measured intensity is very high and for the unflat parts the intensity is almost zero. The problem is that the measurement of the 3D scanning needs enough reflected light to determine the exact depth. Low intensity values can lead to wrong depth measurement, which is a disadvantage. If now all groove centers and groove tops were perpendicular and flat, the brightness picture could be used to distinguish the groove center from the groove sides and, thus, to determine the sound information. However, this is not the case since the surface of the aluminum disc contains a lot of wrinkles that lead to an almost useless intensity image.

Figure 17 illustrates the relation between the measured depth (in red) and the intensity (in brown) of an aluminum disc. It is visible that there is no clear connection between them.

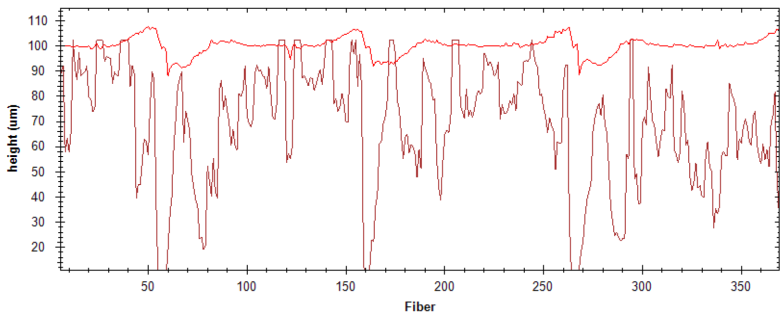

Figure 17: Depth and intensity relation for aluminum discs

4.2.3 Groove

As it is known from the common disc records, the groove of the aluminum disc carries the sound by its distance changes according to the center. By following the groove in time, the needle generates the sound out of the horizontal movement.

Due to the material, the groove of the aluminum disc has to be embossed. Cutting the disc, as it is done for other disc types, is not possible since the soft aluminum would rather be ripped than cut. One particular difference between the two techniques is that the cutting removes the groove material, whereas the embossment just pushes it to the side.

Applying the embossing technique rather than the cutting leads to main differences in the groove characteristics:

- Uneven groove top
- Groove sides with lobes
- Groove depth
- Groove shape

According to this, the typical groove of the aluminum disc is quite different to other discs containing cut grooves. Figure 18 shows this by illustrating a comparison between the aluminum disc groove and a shellac disc groove.

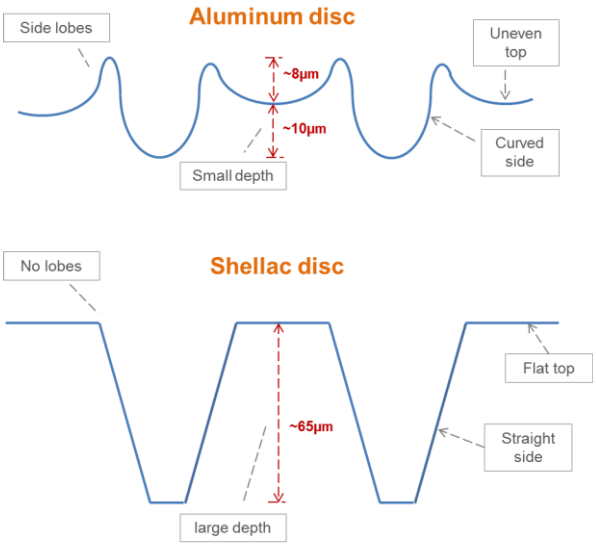

Figure 18: Comparison between aluminum disc groove and shellac disc groove

Although the overall groove structure of the aluminum disc is known, a lot of variations could be observed in the 26 sample discs. A reason for these differences certainly is the non-industrial recording of the discs in the Milman Parry collection. The pressure on the discs during the embossment, for example, or the sharpness of the extruding tool might not always have been identical. In order to present the found varieties in more details they are classified into the four earlier mentioned particularities of the aluminum groove.

Groove tops

Compared to cut discs, the top of the aluminum discs are not flat. This is due to the two auxiliary lobes that create a U-formed groove top. Depending on the lobes, the top is more or less shaped like a U. By analyzing the groove tops of the 26 provided discs, it could further be observed that noisiness is varying a lot: not necessarily from one disc to another, but on the same disc as well.

Figure 19 and Figure 20 present the differences found in the groove top noise in the 26 sample discs.

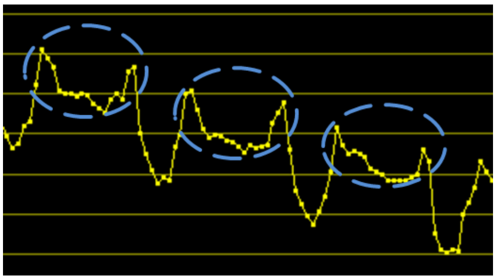

Figure 19: Less noisy groove top

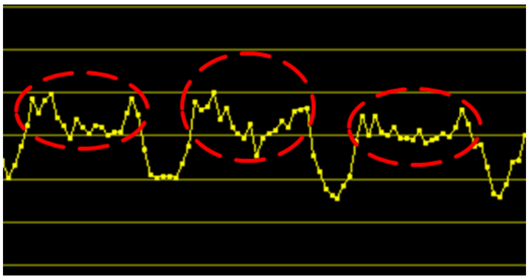

Figure 20: Noisy groove top

Side lobes

Similar to the groove top, the groove lobes differ a lot. However, the differences occur mainly between the discs and not on the same disc. This makes sense since the lobes are related to embossing conditions that usually remain unchanged for one disc. It could further be observed that one lobe among the two of a groove is usually bigger than the other. The higher side however is not always the same as it could be supposed by considering that centrifugal force.

An example for the found differences in the lobe size is shown in Figure 21 and Figure 22. The size variation between the right and the left lobe of a groove can be seen in Figure 22.

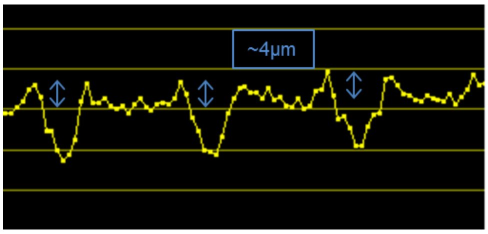

Figure 21: Small groove lobes

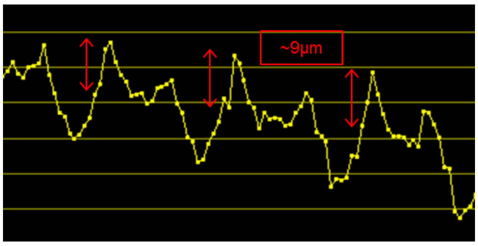

Figure 22: Large groove lobes

Depths

As it was mentioned before, the groove depth varies from 4µm to 15µm in the 26 sample discs. However, most of the grooves are around 10µm. Deep grooves are more likely to distinguish from the top than small ones and are therefore considered to be more suitable.

Figure 23 gives an example for the largest groove. In contrast to this, Figure 24 shows an example of a disc containing a small groove.

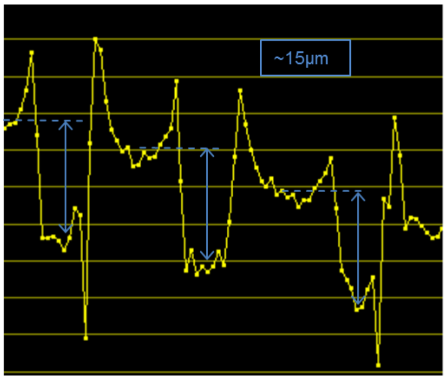

Figure 23: Deep groove

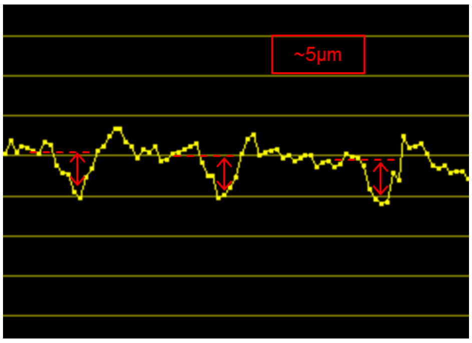

Figure 24: Small groove

Shapes

Compared to cut grooves, the groove shape of an aluminum disc is rather U-formed than V-formed, which is once more due to the embossing and the tool that is used for it. By analyzing the aluminum disc, variations in this U-form could be observed. Figure 25, for example, shows grooves that are clearly U-formed, whereas the grooves presented by Figure 26 tend almost to a V-shape.

Differences may also occur within one disc. In that case the steepness of the groove sides remains similar and the groove bottoms change in particular. It is supposed that this effect rather results from subsequent dust or damage than from the initial recording.

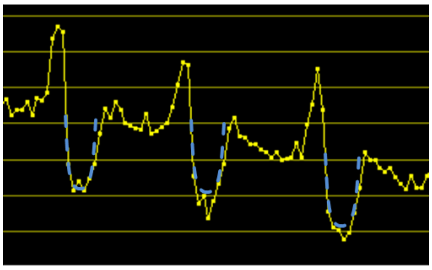

Figure 25: Well U-formed groove shape

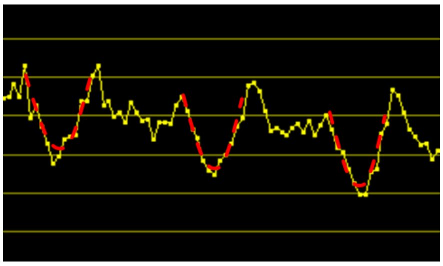

Figure 26: Groove shape tending to V-shape

4.2.4 Damages

Although aluminum discs usually are very likely to be damaged by using inappropriate equipment, especially wrong needles, no such damage could be observed on the discs of the Milman Parry collection. They seem to have been handled with care over all these years. Nevertheless, two types of damage were found on the provided aluminum disc.

- Warped border
- Unidentified stains

The warped border could be identified on one disc, where only one border region is warped. This looks like a damage that originates from a fall on the edge or an impact during a transport. Since the warping is only small, the concerned region can be scanned without problems.

The second observed damage has occurred on several discs. On hazardous positions on different discs some stains resembling chemical burns have been found. At these positions, the groove is no longer perceptible and the sound information therefore lost. The origin of these stains and their evolution could not be determined. Figure 27 shows an example where two stains have been found on the middle of a disc.

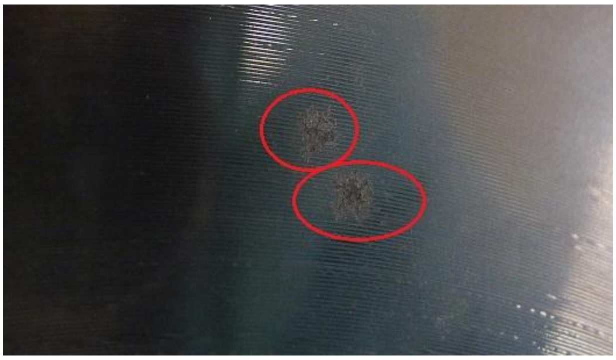

Figure 27: Stain on a disc

4.3 Scanning

Before a data processing algorithm for aluminum discs can be developed, the data has to be acquired with the corresponding LabVIEW software. The initial software was however not designed for aluminum discs, so that a solution, which allows the scanning of the special disc type, has to be found. This subchapter aims to present the required or most appropriate parameters for the data acquiring and the difficulties related to the scan of aluminum discs. Thereby the focus is set on the 3D system because it has been developed for a lot of recordings and therefore contains a lot of adaptable parameters. Another reason is that the 3D scanning is preferred since it is supposed to achieve better results. Nevertheless the scan of aluminum discs with the 2D system in presented at the end of this subchapter.

4.3.1 Parameters

The 3D system allows a lot of adaptations through the variation of parameters. On one hand this is an advantage because different kinds of recordings with their own difficulties can be scanned. On the other hand, the amount of parameters tends to complicate the usage that is particularly difficult for infrequent users. It is also challenging to introduce a new recording type because the best value for each parameter has to be determined. Therefore, this subchapter aims to present the most important parameter values for the scan of aluminum discs.

Tracking

In order to compensate the non-flatness of the discs a tracking has to be applied. The three possible methods are presented in chapter 3.3.1. Tests have shown that the laser tracking leads to the best result. The two other methods, the MPLS and the gathering tracking, do not yield the desirable results.

The MPLS tracking, which determines its z-motor correction from the measured data, has some issues related to the speed used for aluminum discs. The feedback system calculating the height correction is not reacting fast enough and this leads to an oscillation.

The rotation speed is also a problem for the gathering tracking. The height values of the first revolution are well stored in a file and read out for all the passes of the same part of the disc, but the adjustment of the z-motor is not fast enough to remedy the unevenness of the discs. It may even be that the measured non-flatness is bigger than the real one due to this tracking method.

In contrast to the two other methods, the laser tracking is not performed by the LabVIEW program. The measured height of the laser is directly transmitted to the z-motor, which adapts the height according to it. The only thing that has to be considered is that the measuring point of the laser is not at the same position as the focused point of the camera. A script in the XPS system however allows delaying the measured height and to adapt the height offset between them so that this no longer is a problem. The only disadvantage of the laser tracking compared to the gathering is that the each pass of a multiple pass might not have undergone the identical height corrections. Thus, this height differences among the passes will have to be removed later by a post-processing.

Exposure time

Most of the light coming from the light source is directly reflected because of the shininess of the aluminum discs. This can easily lead to the saturation of the measured intensity, which in turn can provoke bad values in the measured height.

In order to capture less reflected light, the exposure time can be reduced. For the aluminum disc the shortest possible exposure time has been determined. All other exposure times lead to intensity responses that were too close or even at saturation. Although the exposure time is a duration, the corresponding parameter requires a frequency value that can be chosen on a knob. Therefore the shortest possible exposure time corresponds to the highest available frequency of 1800Hz.

$$t_{\min\_exp} = \frac{1}{f_{max}} = \frac{1}{1800Hz} = 555.56\mu s \tag{4-1}$$

This short exposure time causes several difficulties related to the rotation speed but at the same time allows lowering the scanning time. Instead of adapting the exposure time it would also be possible to lower the intensity of the light source by a manual knob. Since the time is an important factor, it is preferable to use the possibility of a faster scan.

Pass

In correspondence to the small depths, the groove width of the aluminum disc is relatively small. Since the distance between two measurement points is given (10µm), only few points are carrying the groove information. This is especially problematic for the processing of the data because one wrong point changes the groove structure a lot and thus complicates the determination of the groove center during the processing with PRISM.

In order to bypass this resolution limitation given by the distance between two fibers, multiple passes can be taken for each part of the discs. Thereby the camera is shifted for each pass by a defined section of the fiber distance. The line and coincidentally the groove resolution are therefore directly related to the number of passes.

$$Res_{Npass} = Res_{pass} \cdot nb_{passes} \tag{4-2}$$

Two restrictions have to be taken into account in order to determine the appropriate number of passes. First, enough passes should be taken so that enough groove information is available to locate the groove center with the most possible precision. In that case the more passes taken the better. Second, the number of passes directly affects the acquiring and processing duration. For the time constraint, the amount of passes should therefore be as small as possible. As a result of the test, the best compromise is found by using a 4-pass (Figure 28) for the aluminum discs. In that case each of the pass should be shifted by a quarter of the point spacing, 2.5µm.

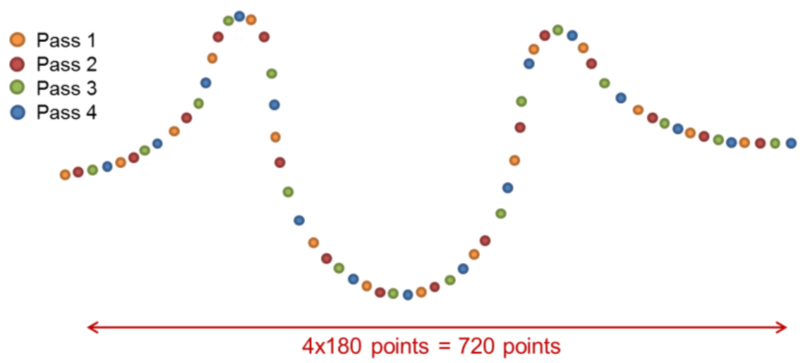

Figure 28: 4-pass illustration

Readout

Another important parameter is the number of readouts per revolution. This value determines how many times the LabVIEW code retrieves the collected data from the XPS system in 360°. This data is then used for monitoring display in the scanning program and is stored into a binary file that is later loaded for the processing.

A common readout value is 1000 which means that every 0.36° data is retrieved from the XPS system into the 3D acquisition software. Due to the high rotation speed of the aluminum disc, this frequent readout comes up against limits because the monitoring is not fast enough (detailed explanation in chapter 7.2). For this reason a lower readout of 10 reads per revolution has been determined for the aluminum disc. The low readout however entails that the monitoring display refreshes only 10 times per revolution, which is not enough to observe the scan directly. Nevertheless, it is the price to pay for a considerable data quality.

Overview

As an overview, the parameters with their determined values as explained above are presented in the following table.

Parameter	Value/Method
Tracking	*Laser*
Exposure Time	*1/1800s*
Pass	*4*
Readout per revolution	*10*

Besides the mentioned parameters, there are other important ones that have been ignored because their values are not specially related to the aluminum discs and could therefore also be used for other disc types. The following table shows the applied values accompanied by brief explanations.

Parameter	Value/Method	Explanation
Compute Z mean	*None**	*Determines how the mean value is calculated when the MPLS tracking is used.*
Dphi	*0.01°*	*Angle that determines how much samples are taken during one revolution. (* $nb_{samples} = {}^{360°}/_{Dphi}$*)*
Phi start / end	*0° / 360°*	*Phi start and stop define the beginning and end of a revolution (allows acquisition over for example only 180°).*
Phi init step back	*60°*	*Angle that has to be gone back before measuring. Allows the motor to accelerate at the determined velocity.*
dZ	*1800µm*	*Covered width in one revolution.*
dZ npass	*2.5µm*	*Shift between the passes. Since 4-pass is used for aluminum discs, the 2.5µm are given.*

**not needed since laser tracking*

Due to the fact that the *Dphi* parameter is determined, the sampling frequency of the aluminum discs can now be calculated with the Equation 3-6 that has been presented chapter 3.3.1.

$$f_s = \frac{360°}{0.7692\frac{s}{rev}} \cdot \frac{1}{Dphi} = \frac{360°}{0.7692\frac{s}{rev}} \cdot \frac{1}{0.01} = 46.8kHz \qquad (4\text{-}3)$$

4.3.2 Modifications

The difficult surface and shininess of the aluminum disc led to scanning problems which could not be solved by simply adapting program parameters. Investigations were necessary in order to introduce new calculations and new parameters that allow a correct scanning.

Finding focus

A first investigation has been made in the part of the 3D program trying to find the optimal focus on the disc by adapting the z-motor and, thus, the height of the camera. This stage is used before the initialization of the laser tracking as well as at the beginning of the MPLS of gathering tracking.

The initial finding focus method uses only the median value of the scanned surface to determine when the focus is all right. A median value being beneath the threshold, given as parameter, assumes the surface to be in focus. This is possible since the height values are all maximal (350µm) if the z-motor is at the start position and the disc out of focus.

This principle however is not good enough for the aluminum discs, since the measured height positions are not always maximal until the focus is reached. During the finding focus process, some values may also very low (<100µm). This entails that the median value is possible to be lower than the threshold value. Thus, the focus should be found even if that does not correspond to the truth.

A second threshold has been introduced which takes into account the standard deviation of the measured heights. If now the first median height threshold is satisfied with a large standard deviation, as it is the case for the wrong results, the program remains searching until the standard deviation threshold is also satisfied.

In order to introduce this supplementary threshold, the calculation of the standard deviation has been added in the processing part of the measured data in the corresponding LabVIEW files, so as to avoid finding such an incorrect focus.

Concerned files
3D-Tools_scan-NEW.vi
3D-Tools_viewer-DC.vi

Height adjust

Another modification has been made for the height adjustment of the 3D acquisition software. A value in an algorithm has not been set back, so that an occurred problem in the height correction could never be solved.

The problem however has no direct impact on the scan of aluminum discs because the erroneous section was related to the MPLS tracking, which is not used for aluminum discs. Nevertheless, the correction has been implemented in the corresponding LabVIEW file.

Concerned file
3D-Control-TEST-V3-DISCRotation_marc_adjustFocus.vi

4.3.3 Difficulties

Scanning aluminum discs with the 3D system is related to two major difficulties that have to be dealt with. One is the amount of bad points and the other the duration of a disc scan.

Bad points

Compared to other disc types, the scan result of the aluminum disc contains a lot of bad points. One of the reasons certainly is that the captured intensity values show big differences. At the same time some points are almost saturated and others are almost zero. Both of these situations are vulnerable for bad points. Another reason for bad points are weak or ailing fibers. This however is not depending on the disc type.

The main problem with the bad point is that they can do a lot of harm during the data processing, when lines or quadratic curves are fit into the groove. One bad point can completely falsify the result and this finally might be audible in the generated audio file. Figure 29 shows an example groove cross section containing three bad points (encircled in red).

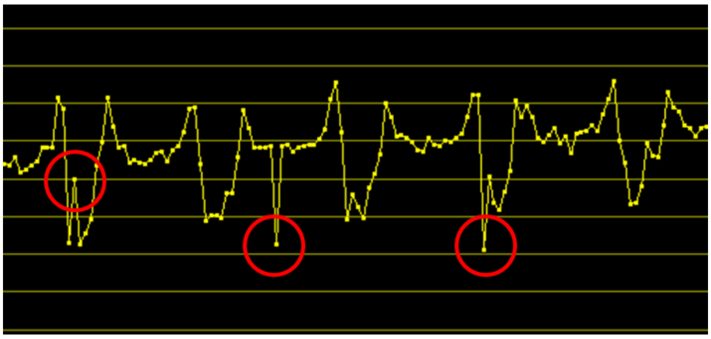

Figure 29: Bad points

Scan duration

It is known that the 3D disc scan is more time-consuming than the 2 dimensional. Due to the parameter decision of using four passes, this comparison is even getting worse. Time measurements have shown that scanning one side of an aluminum disc with the presented parameters (chapter 4.3.1) takes approximately 2 hours.

If it is supposed that all the about 3000 discs of the Milman Parry collection ought to be scanned, the required amount of time would be:

$$t_{total} = t_{side} \cdot 2\frac{side}{disc} \cdot n_{discs} = 2\frac{h}{side} \cdot 2\frac{side}{disc} \cdot 3000disc = 12000h \qquad (4\text{-}4)$$

A person working 40 hours a week, 47 weeks a year would thereby need to scan during:

$$t_{work} = \frac{t_{total}}{t_{work}} = \frac{12000h}{47 \cdot 40\frac{h}{year}} = 6.38\ years \tag{4-5}$$

This short calculation points out the importance of the scanning duration. Nevertheless, it is not possible by now to perform faster 3D scans leading to good result. In order to reduce the duration, further investigations have to be made in the principle of the 3D scan. An example would be a continuous acquisition of the data as it is done by the 2D system instead of rotating back for every pass.

4.3.4 2D scan

Besides the 3D scanning, the aluminum discs can also be scanned by the 2D technique. However, this method has been less taken into account due to previous investigations that predicted bigger potential for the 3D approach. Nevertheless, the method is considered at least for comparison purposes.

Parameter

Compared to the 3D system, the 2D system has specifically been designed for disc recordings and has passed through a longer evolution. Due to these to facts, the data acquisition could be maximally automatized for the specific use. This finally results in a less complicated utilization and less parameters that have to be determined for a new disc recording.

In the following table the parameters of the 2D system are presented with its determined values for aluminum discs accompanied by short explanations.

Parameter	Values	Explanation
Aperture (0 - 4)	*4*	*Aperture number of the camera lens. Has no influence on the comportment of the acquisition; just for the labeling.*
Intensity (0 - 100)	*1-15*	*Intensity value has to be low since the aluminum discs are very shiny. Depending on lighting and disc, the value should be adapted; top lighting: 1-5, side lighting 4-15.*
Exposure (100 - 300)	*100*	*Exposure time determining the time of lightning. The minimum is defined for aluminum discs because of the shininess.*

Lighting

As presented in chapter 3.2.1 the 2D technique allows scanning disc by guiding the light from three different directions: the usual top lighting, the side lighting from the inner side of the disc and the side lighting from the outer side. The three possibilities allow getting alternative results if for example the groove bottom, which is reflecting at top lighting, is not of good quality.

Since the groove structure of the aluminum disc is varying a lot, it cannot with certainty be said that one of the lighting is better than another. It always depends on the disc to be scanned.

Aluminum discs containing a deep groove, for example, are more responding to top lighting. The reason for this is that their groove sides are usually very steep and the groove bottom rather flat so that the transition between them is quite radical. Thus, the transition between bottom and side is well defined in the reflected light, which leads to sharp edges on the intensity image.

For the majoritarian small grooves however, the top lighting is not ideal because the groove bottom-side transition is rather fluent than radical. This fluentness will also be found in the resulting gray scale image, which makes edge detection very difficult. Therefore, side lighting is a better solution for the small groove aluminum discs.

However, it has to be noted that the result with inner side lighting can differ a lot from the outer side lightning. The reasons for this are the side lobes that are usually not at same height and therefore not reflected the same way.

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5 Implementation

After the investigations that have been performed on the characteristics of the aluminum disc in order to find appropriate ways to scan them, it is now time to extract sound from the generated binary files containing the depth and brilliance information. This reconstruction of the sound is done by the PRISM software that has not been adapted for the special aluminum discs yet. Therefore, this chapter aims to explain the changes and modifications that have been added to the software in order to be able to process aluminum disc data. In a first part, the difficulties and challenges related to this disc type are discussed, before in a second part the existing approaches in PRISM are presented. The third part finally explains the implemented approach for the aluminum discs in detail.

5.1 Requirements

Aluminum discs, similar to most types of disc records, carry the sound information in the horizontal movement of the groove. In order to be able to reconstruct the sound, the work performed by the needle during the common phonograph playback has to be simulated digitally. Since the needle basically follows the groove, it aims to find the precise groove center position for each sample taken with the 3D acquisition software. By stringing the found center positions together, the theoretical position of the needle is found. However, the absolute needle position has further to be derived in order to obtain the needle movement and thus the actual sound.

Due to the fact that the center positions are indispensable for sound reconstruction of disc recordings, its determination is the essential point of the PRISM software. The more precise this groove centers are identified for each sample, the closer the sound is going to be to the reality and the lower the noise is going to be.

This search for the precise center is at the same time the biggest challenge for the introduction of the aluminum disc type to the PRISM software. Due to the large differences compared to common disc types, some of the used properties can no longer be taken into account and new ones have to be considered. The following table points out the challenges on these properties.

Property	Challenge
Slope	*The two straight slopes of the V-formed groove do not exist on aluminum discs. This means that no linear functions can easily be fit into the slope in order to define the steepness, to find outlier points or to find the groove bottom or top.*

Groove top	*The groove top is no longer flat so that the groove itself is more difficult to find. Furthermore, there is no known reference value that would allow easily the merging of multiple passes or multiple revolutions.*
Bad points	*The amount of bad points is high for scans of aluminum discs. Therefore, improved or appropriate algorithms to determine the bad points have to be found.*
Small groove	*The small grooves of the aluminum discs involve the need of multiple passes. Therefore, the merge and match of them becomes very important and should not be influenced by bad values.*
Lobes	*Some of the aluminum discs contain very high and well-formed side lobes, which continue the groove shape. In this particular case, the lobes could provide additional information for the determination of the groove center.*
Bad brilliance data	*Due to the fact that the groove is not really defined in the brilliance data, this data is not very useful for the determination of bad points or groove centers.*
Variety	*A lot of varieties exist among the aluminum discs. Therefore, the algorithms determining the groove centers have to be flexible rather than rigid.*

All these factors have to be considered during the development of a new algorithm that allows processing the aluminum discs in order to find an appropriate way to identify groove center with the biggest possible precision and, thus, the best possible quality of the reconstructed sound.

5.2 Existing approaches

The PRISM software contains an existing amount of already implemented algorithms that allow determining the groove center of different disc types with different qualities. The following subchapters aim to present the basic ideas of each of them. [6][7]

5.2.1 Fit

The idea of the fit algorithm is to take advantage of the sloped groove sides in order to determine the groove center. Therefore, a linear regression of both sides is calculated. The interception of the two resulting linear functions is then assumed to be the center as is shown by the yellow line in Figure 30. In order to get the precise groove center, this principle needs scans and discs of good quality because bad points can easily displace the groove center to a completely wrong place.

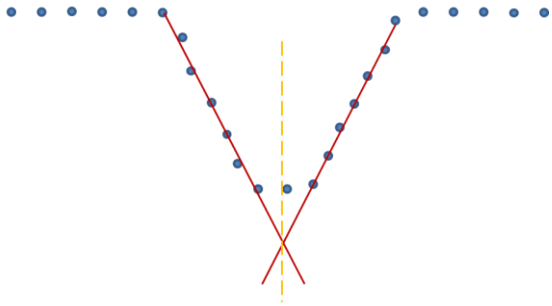

Figure 30: Groove center determination with Fit algorithm

5.2.2 Fit-Line

The fit-line algorithm is a further development of the fit algorithm. Instead of considering the interception of the two linear functions calculated from the groove sides as groove center, it uses the two lines as point of departure for another step. This further step attempts to fit a horizontal line of a defined length into the V-form generated by the two lines. It is as if the horizontal line was dropped in the groove. At the point, where the sides of the V-form stop the line, the middle of the line determines the groove center. Figure 31 illustrates the principle of this method, where the green lines represent the fitted linear functions, the red line the dropped horizontal line and the yellow line the determined groove center.

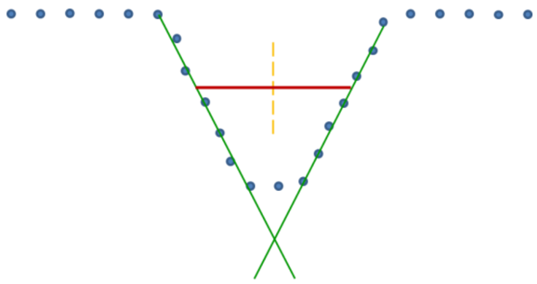

Figure 31: Groove center determination with Fit-Line algorithm

During the years this methods has been improved, so that three algorithms using this principle are implemented in the current PRISM version. The following table presents them with the added modifications.

Algorithm	Modifications
Fit-Line	*Original version*
Fit-Line V2	*Modifications on the detection and correction of bad slopes in order to reduce the amount of wrong defined groove centers. Furthermore, the interpolation of bad groove centers has been introduced.*
Fit-Line VM	*Adaptation on multiple pass scans; The new version takes advantage of the reference height of 100µm at which the groove tops are placed during the match of the multiple passes. Furthermore, additional processing to remove more bad point has been introduced.*

Due to the evolution, the fit-line method is considered to be robust and reliable compared to other algorithms.

5.2.3 Quad

The quad method is an idea that was originally used for the extraction of cylinder recording and not for discs. Instead of fitting the linear functions to the groove sides, it searches for a parabolic function that fits the groove. Thereby, the function's minimum determines the center of the groove as it is illustrated in Figure 32. Since the groove of cut discs does not really correspond to a parabolic function, this method is not optimal and less used than the fit-line algorithms.

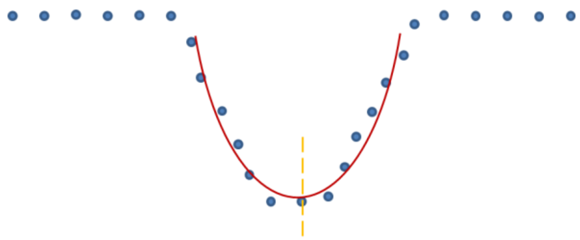

Figure 32: Groove center determination with Quad algorithm

5.2.4 Derivative

The derivative algorithm uses a different approach than the ones presented before. The reason is that it does not directly determine the groove center in order to reconstruct the sound, but that it determines the difference from one groove sample to the next. Therefore, the difference of each point, from one sample to the other, is observed. When the groove moves, the difference is large and if there is no movement the difference is nearly zero. In order to get some redundancy and, thus, a more precise result, the same is done with the intensity points.

Figure 33 shows an example of this algorithm on the depth data, where the green points belong to the previous sample and the blue ones to the current. Due to the position changes of each point it can be said that the groove moves to the right.

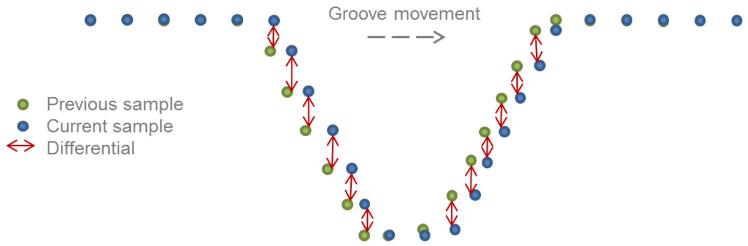

Figure 33: Principle of Derivative algorithm (only depth image)

5.3 Decision

The already implemented groove detection algorithms provide some ideas on which the new algorithm allowing the processing of aluminum discs can be based on. However, due to the different groove characteristics of this new disc type, some approaches are less promising than others.

The most famous and evolved approach for common cut discs, the fit-line algorithm, seems not to be as appropriate for the embossed aluminum disc. The reason is the different groove-shape that is rather U-shaped than V-shaped. Due to the non-linear groove sides, the fit of a linear function is less likely. Depending on the considered points, the resulting function can vary a lot and by that falsify the determined groove center position. Furthermore, it would be problematic to define the bad points among the considered points for the linear regression because correct points might be as far from the calculated linear function as the bad points. Based on the inappropriate initial situation for the aluminum disc groove shape, the idea of a fitting linear function to the groove sides is put aside.

In contrast to the fit and fit-line algorithms, the derivative algorithm is not sensible to the groove shape of a recording and might therefore be an approach for the aluminum discs. The problem however is that the derivative algorithm uses the intensity values for the calculation and these values are known to be bad for the aluminum disc scans. One may now say that the depth information should be enough, but with the big amount of bad points the calculations and the precise movement determination are predicted to be difficult.

The last principle is the fitting of a quadratic function to the groove. This approach is very inappropriate for the V-shaped disc grooves for the same reasons as the line fitting algorithms are inconvenient for the aluminum disc grooves. For U-shaped grooves, however, the quad algorithm seems to be very adequate and does not obvious drawbacks. For this reason, the principle of fitting a parabolic function to the groove is chosen for the aluminum discs. The existing quad algorithm is however very basic and designed for uncomplicated and simple cut grooves, so that only its principle can be inherited.

Other approaches without existing implementation in PRISM have also been considered. One idea for example, is to fit a high order polynomial function to an entire line containing several grooves. The local minima of this function would then be the groove centers. Another idea is to generate an average trace without any movement. It would then be placed over the actual groove so that the movement, and thus the sound information, is obtained in the difference to the averaged groove. None of the ideas however has been taken into further account because processing entire line or disc information introduces new problems as dealing with bad points on the groove tops or non-straight average grooves in time.

5.4 Processing of aluminum discs

The approach that has been chosen for the aluminum disc processing is the fitting of a parabolic function into the groove so that the groove center is given by the minimum of the function. However, determining the center position out of the depth information is associated with a lot of intermediate steps. In order to get the best possible result, all these steps have to be adapted or introduced for the aluminum discs.

In order to present the processing of the aluminum disc in PRISM, this chapter first provides an overview of the implemented principle before each step is pointed out in detail. Additionally, the introduced adaptions on the GUI as well as some unsuccessful ideas are presented at the end of the chapter.

5.4.1 Principle

In order to process the aluminum disc scans, the PRISM program structure must be preserved so that the processing of other recording types remains unchanged. Through that condition the global principle for the aluminum discs is given. The different steps however are completely independent and had to be adapted or introduced for the aluminum discs. By presenting the new program flow chart in the case of aluminum discs and the related classes and methods, the principle of the new processing should become clear.

Program procedure with aluminum discs

The basic principle of the program procedure has been presented in chapter 3.3.2. As explained before, this procedure allows processing different recording types and attempts to be modifiable so that new types can be introduced without the need of changing the entire program structure. Therefore, only two steps of the initial flow chart (Figure 12) are concerned with the introduction of the aluminum disc processing. Figure 34 shows them in orange.

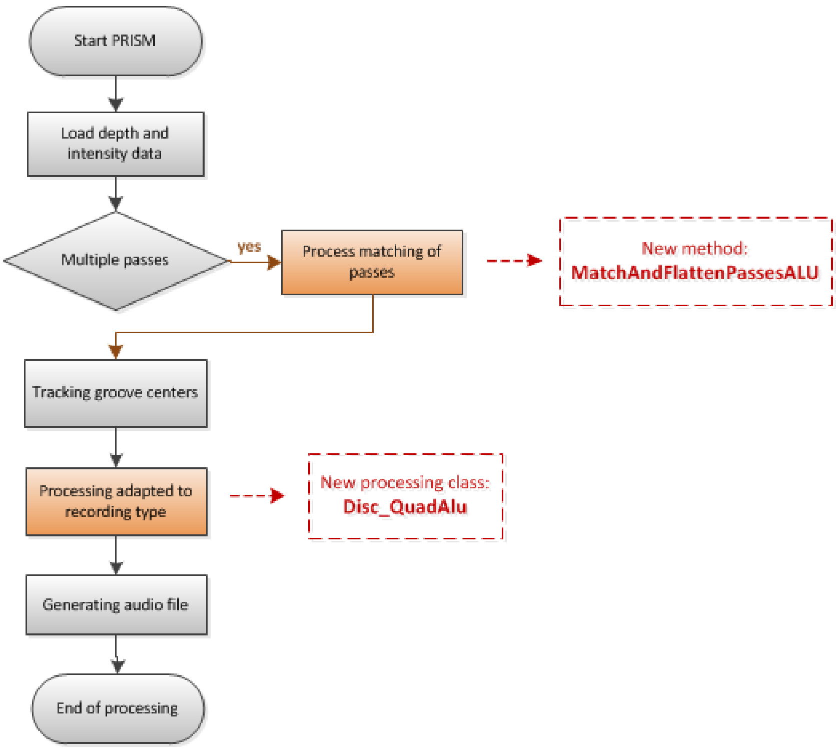

Figure 34: Modified steps in PRISM program procedure

The flow chart shows that there is no decision about the multiple passes; the matching of the passes is done anyway. This is due to the fact that the aluminum discs are meant to be scanned with four passes. In that step the passes, even if there are more or less than four, are adapted to each other, so that no height differences are contained between the passes in the resulting merged image. Since the structure of the aluminum disc is quite different to other disc types, a separate algorithm had to be introduced by adding a new method; the *matchAnd FlattenPassesALU*.

New processing part

The match passing step does prepare and correct the data for the actual processing that is done in the step *Processing adapted to recording type*. For the processing of the aluminum disc, a new class has been introduced to this step; the class *Disc_QuadAlu*. This class is responsible for the entire processing of the new recording type as well as the corresponding display and subdivides the processing step into further steps as shown by Figure 35.

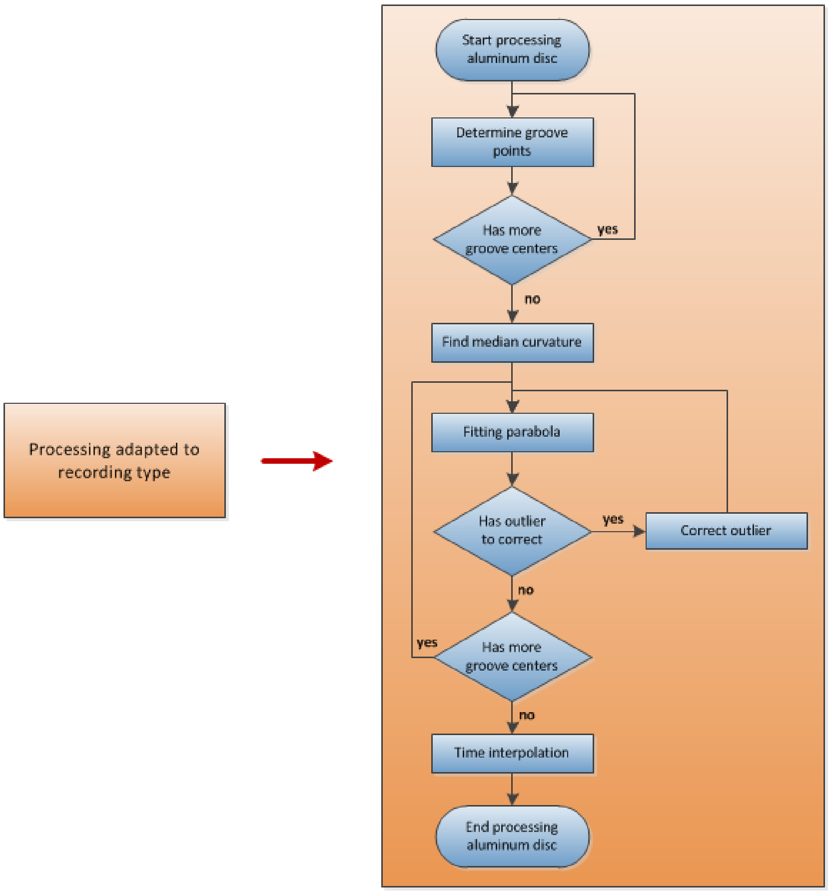

Figure 35: Processing principle of aluminum discs

Due to the tracking that is performed before the processing, an estimation of the groove centers is already available at the moment of the groove processing. Thanks to this, the number of groove samples in time and their approximate position is known so that one after the other can be handled.

As shown in the procedure flow chart for aluminum discs (Figure 35), the first step is to define the points of the each groove sample. By looking for a local minimum in the groove, a groove center estimation is searched, that is better than the one given by the tracking. The found minimum determines furthermore the points that are considered for the further calculations by marking the same amount of points on the left and right groove side.

By having the points for the calculation determined, a first fitting of a parabolic function into these defined points is performed. However, the resulting 3rd order function is only used for the curvature information. By taking the curvature of all groove samples, the median groove curvature is then calculated.

During a second pass through all the groove samples in time, it is attempted to fit the calculated median curvature into the determined groove points. Since the curvature is given, only the horizontal and vertical position can be adapted, which is similar to what actually happens with the needle in the groove. In order not to be influenced by bad points in the groove, the most outlying points are replaced by less disturbing ones while placing the function with median curvature into the groove. The exact minimum of the placed parabolic function finally determines the groove center position for the current groove.

Due to the fact that some of the centers cannot be correctly determined for reasons of dirt or other disturbances, an interpolation is performed at the end of the processing before the audio file is generated.

Class *Disc_QuadAlu*

As has been explained before, the class *Disc_QuadAlu* is the one that is responsible for the actual processing of the aluminum discs. It extends the abstract *Disc* class, which is a base for all the disc recordings and itself extends the abstract *Hardware* class that is the fundament for all recording types. In order to process all recording types, the latter class forces its extending classes to implement several methods, of which only two are really relevant; one that allows the processing (*process()*) and one that allows displaying the processing results (*profile_Paint()*).

Figure 36 presents the structure of the *Disc_QuadAlu* class and shows its relations with the simplified classes *Disc* and *Hardware*.

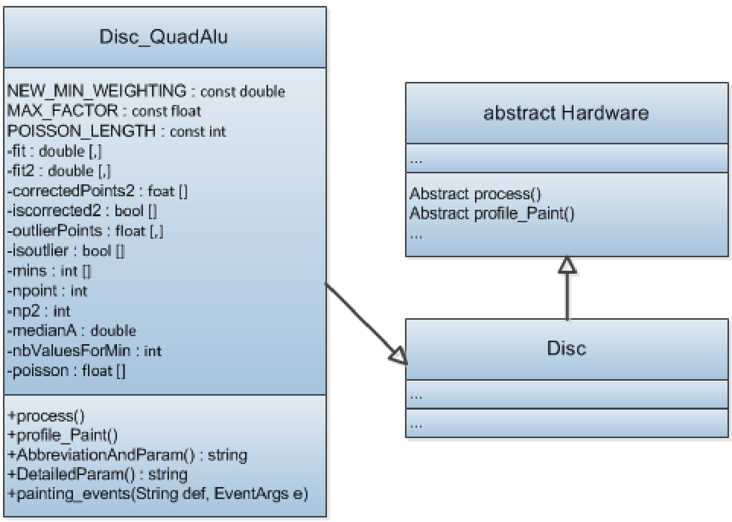

Figure 36: Class Disc_QuadAlu

5.4.2 Match passes

The match pass algorithm aims to adapt the data of the multiple passes. In order to present this, the existing match passes as well as the new implemented algorithm and its detailed procedures will be pointed out in this subchapter.

Existing match passes

Due to the fact that multiple passes are not only used in the case of aluminum discs, there had already been a class handling this problem for scans of cut discs before aluminum discs were introduced. The following table gives an overview of the already implemented methods of the class *MatchPass* that has been adapted over the years and can be chosen during the program execution.

Method	Explanation
Match (matchPass)*	*Adapts the height differences between the passes in a very basic way.*
MatchV2 (matchAndFlattenPasses)*	*Calculates a linear regression of the groove tops in order to find and flatten the height differences between the passes.*
MatchV3 (matchAndFlattenPassesV3)*	*Same principle as Match Pass V2 but instead of just flatten the passes to the median height it is flattened to a constant height of 100µm.*

** Name of method in code*

The *MatchAlu* algorithm

For the multiple passes adaptation of the aluminum discs, none of the three already implemented methods is of use: the first one contains a too basic calculation, the two other methods take into account the groove tops, which are not flat and therefore not easily definable in the case of the embossed aluminum discs. Furthermore, the algorithms *MatchV2* and *MatchV3* are using the intensity value to determine if a point is bad. Since the intensity data is not reliable in the case of the aluminum discs, this intensity consideration could cause problems. For reason of possible difficulties, the new method *MatchAlu,* or, as the function is called in the code, *matchAndFlattenPassesALU*, has been added to the class *MatchPass*. Figure 37 shows its procedure designed for the groove of embossed discs.

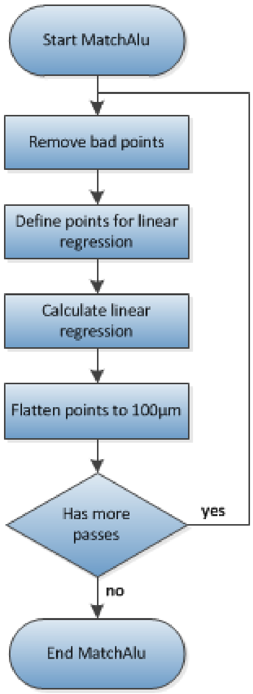

Figure 37: Procedure of MatchAlu

The presented procedure is performed for each pass sample of 180 points of the entire disc. Thereby, the algorithm is able to process all kinds of multiple passes as well as single passes even though the four pass was determined to be optimal for the aluminum disc scans.

Remove bad points

A first step of each pass sample (180 points) before performing any calculation or adaption is the removal of the bad points. This is necessary because bad points may have a big impact on the later linear regression calculation, which would lead to improperly and unevenly merged passes in the final image.

In order to distinguish the bad from the suitable points, the two following conditions for good points are established:

- A point must not differ much from the neighboring ones
- A point must not be far away from the median value of the line (180 points)

Both conditions aim to determine an outlying point between two correct ones. The first condition uses a simple relation between three points in order to decide whether a point is good and can remain or is bad and has to be corrected. Therefore, the average distance between the two outer points and the point in the middle are calculated first before comparing the average value to the difference of the two outer points and a threshold value. If the average distance to the middle point is larger than the threshold and the difference between the outer points, the middle point is considered as bad point. Figure 38 illustrates such a situation with p_0 to p_2 as considered points.

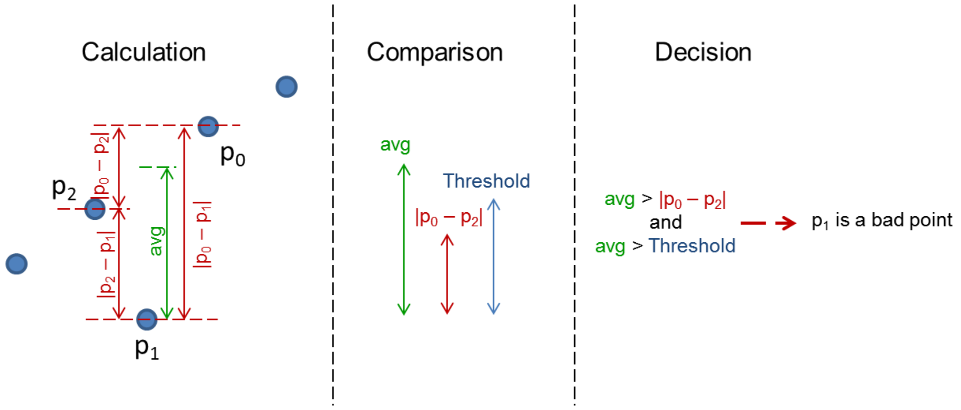

Figure 38: First condition to detect bad points

The second condition uses the standard deviation calculation and the median value in order to determine the bad points. Every point that is further away from the median value than a given factor times the standard deviation is determined to be bad. The following formula shows the condition mathematically.

$$k \cdot \sigma_p < |p_i - \tilde{h}| \tag{5-1}$$

k: *constant to define*
σ_p: *standard deviation of the heights (current line)*
p_i: *heigth of current points*
$\tilde{h}$: *median of heights (current line)*

However, in the first as well as in the second condition, bad points are only replaced if their two neighbors are considered to be good. This latter condition is necessary since the corrected value of the bad points is calculated by taking the mean value of the two neighbor points as shown by the following formula.

$$p_{i\_replaced} = \frac{p_{i-1} + p_{i+1}}{2} \tag{5-2}$$

Since good points surround most of the bad points of a line, the majority of bad points is suggested to be replaced by the two mentioned conditions.

Define points and calculate the linear regression

After replacing the isolated bad points, it may occur that the line still contains non-isolated bad points. As they might influence the result of the linear regression to a great extent, they are discarded for the calculation. In order to define the points to discard, the second condition used for the correction of bad points, shown by Equation (5-1), is applied again.

The points that are considered to be good are then used to calculate the linear regression of the line. Figure 39 shows an example of that step of *MatchAlu.*

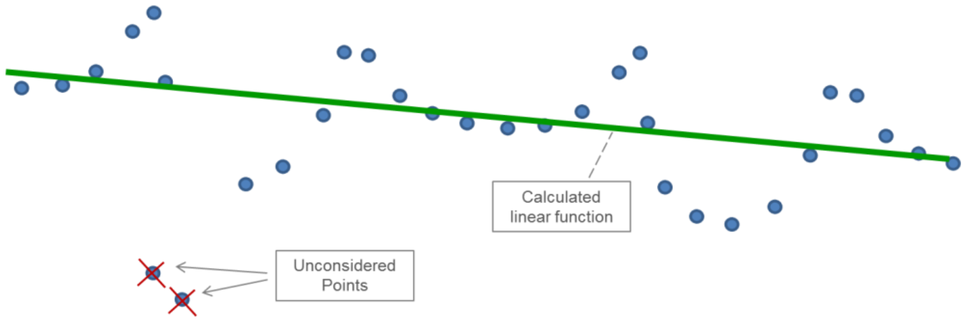

Figure 39: Example the calculated linear regression

Flatten to 100µm

At the end of the *MatchAlu* algorithm all pass samples of 180 points are flattened to a height of 100µm. Therefore, all the points are multiplied by the negative slope of the calculated linear function and subtracted from the difference to the height of 100µm. Figure 40 shows this principle with the linear function in green, the negative sloped function in red and the 100µm height line in yellow.

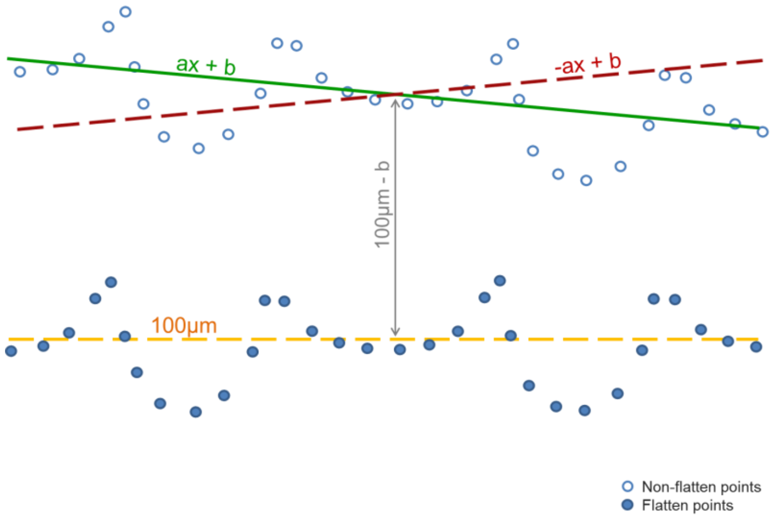

Figure 40: Flattening principle

Mathematically, the flattened points are calculated as follows.

$$p_{i\_flatten} = p_i \cdot (-ai) + (100\mu m - b) \tag{5-3}$$

$p_{i_{flatten}}$: *new point value*
p_i : *initial point value*
a : *slope of calculated linear funtion*
b : *y − intercept of calculated linear function*

Example

Figure 41 presents a comparison between the existing MatchV3 algorithm and the specifically for the aluminum disc developed MatchAlu. It can be seen that, contrary to the MatchV3 result, the MatchAlu result contains no continuous zigzag-shape that is related to a bad matching of the passes.

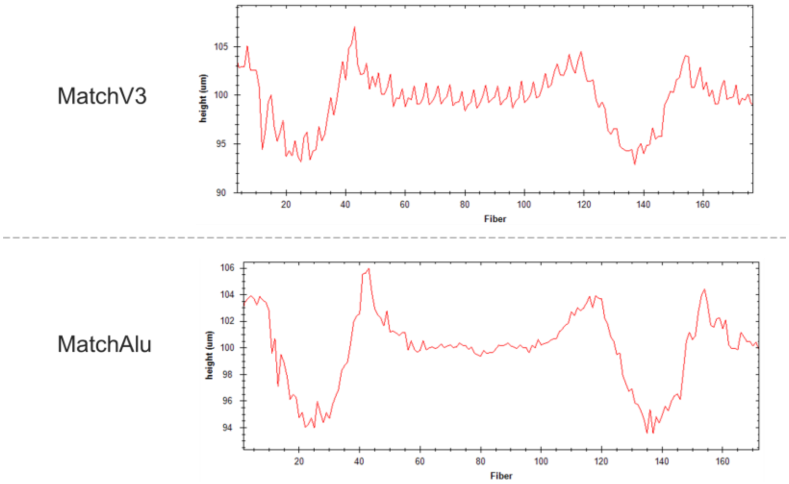

Figure 41: Comparison between MatchV3 and MatchAlu

5.4.3 Determine groove points

Once the multiple passes are merged together and brought to a common height, the groove tracking is performed by the PRISM software. This step is independent of the disc type and had therefore not to be adapted for the aluminum discs. Nevertheless, it is inevitable because it provides a first estimation of the groove positions and the exact number of groove samples that is going to be used for the sound reconstruction. The blue lines in Figure 42 show examples of this groove tracking.

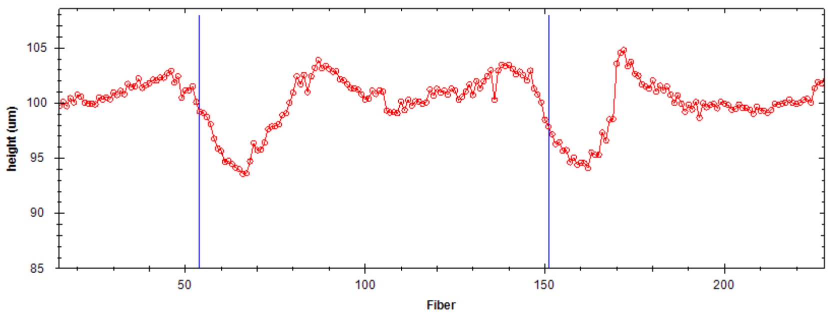

Figure 42: Groove tracking

By having only an estimated position of the groove, the groove points that are going to be considered for the fit of the parabolic function have to be defined. This is performed in three steps:

1) Finding the local minimum
2) Weighing with previous minimum
3) Defining groove points

The following subchapters present the work of each of these three steps.

Finding the local minimum

Since the groove tracking is mostly located in the groove sides or even on the groove top, a better estimation of the groove has to be found. This is done by searching the groove bottom with an algorithm that finds the local minimum.

This algorithm takes the tracking position as a starting situation and defines a range from minus the number groove points to plus the number of groove points. The minimum is searched in this range by always determining the maximal value of a defined number of points. At the end, the lowest maximum value determines the local minimum. Following pseudo code describes this search.

```
min = trackedPoint
rangeStart = trackedPoint – nbGroovePoints
rangeEnd = trackedPoint + nbGroovePoints
For all points between rangeStart and rangeEnd{
      max = max value in current nbPointsForMin points
      if max is smaller than previous max
            min = current point
}
```

Due to the fact that the algorithm calculates the maximum out of a certain number of points (`nbPointsForMin`), the local minimum is not just defined by the smallest point value that may be a remaining bad point. However, this number of Points (`nbPointsForMin`) is not fixed but changes with the number groove points, as the following pseudo code shows

```
nbPointsForMin = ceiling(0.15 * number of groove points)
If nbPointsForMin is even
      nbPointsForMin = nbPointsForMin – 1
If nbPointsForMin is smaller than 3
      nbPointsForMin = 3
```

Weighting with previous minimum

Once the local minimum point is determined, it is weighted with the previous minimum points. The reason of this step is to avoid two following local minima to be at a completely different position, which corresponds to a jump in the groove. Since the common sampling frequency is 46.8 kHz, such groove jumps are not realistic.

By taking into account the previous local minimum these non-realistic cases can be reduced and, thus, the determination of false groove center points can be avoided. Since the reliability of a calculated local minimum reduces with its distance to the previous minimum, the introduced weighting aims to do the same: the further the calculated minimum is away from the previous one, the more the previous minima decides about the current minima. Figure 43 shows the implemented distribution that weights the current local minima.

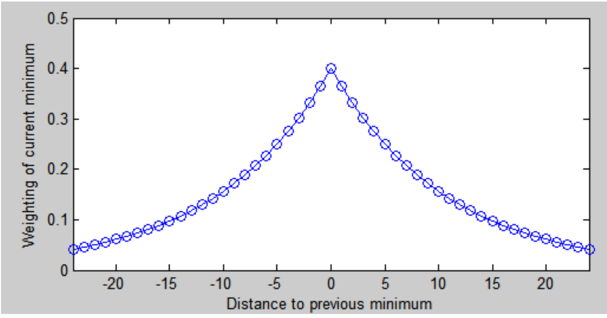

Figure 43: Weighting distribution for number of groove points equal to 35

Since the maximum of the distribution function is 0.4, the previous minimum is always more weighted than the current minimum. Following formula illustrates the calculation determining the weighted local minimum.

$$weight = dist(min_i - min_{i-1}) \tag{5-4}$$

$$min_i = round\big(min_i \cdot weight + min_{i-1} \cdot (1 - weight)\big) \tag{5-5}$$

The length of the distribution is determined by a constant to 49. For all distances between the current and the previous local minimum that exceed the distribution borders, the smallest value of the distribution is taken as weight.

Defining groove points

During the last step, the determined local minimum helps to define the groove points that are used for the further calculations. Thereby, half of the indicated numbers of groove points are marked on each side of the found minimum. As an example, Figure 44 shows such a definition of the groove points with 25 groove center points and, thus, 12 points on each side of the local minimum.

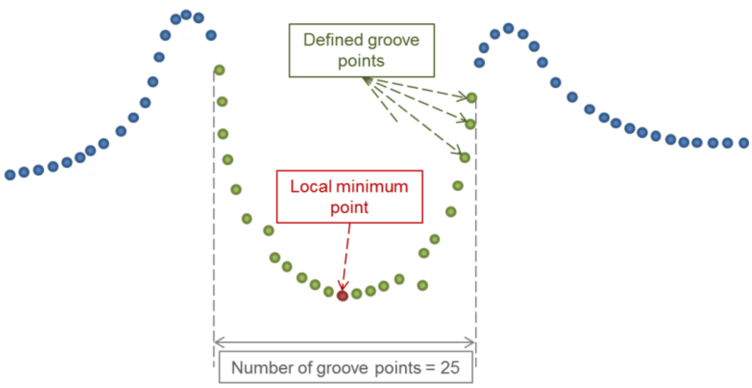

Figure 44: Defining groove center points

5.4.4 Fitting median curvature

In this step the determined groove points are used to calculate a 2nd degree polynomial regression. Instead of calculating the groove center directly from the resulting parabolic function, the calculation is performed over three transitions:

1) Finding fitting parabolic function for each groove
2) Calculating median curvature
3) Fitting parabolic function with median curvature

The first transition involves fitting any parabolic curve into the determined points of all groove samples, as it would have been needed anyway. The resulting function is of the following type.

$$y = ax^2 + bx + c \tag{5-6}$$

However, the curvature a of each fitted parabola is the only function parameter that is used for the further processing; b and c are discarded.

In a second transition, the median curvature of all the previously fitted parabolic functions is calculated before this median curvature is used to perform a constraint fit on each groove sample in the third transition. Since the curvature is given, only two parameters of the quadratic function remain unknown so that the polynomial regression is no more by the 3rd but by the 2nd order. The following formula illustrates this by moving the 3rd order parameter to the known side of the equation. The remaining unknowns b and c can thus be determined by a linear regression.

$$\begin{aligned} y - ax^2 &= bx + c \\ \Rightarrow y_1 &= bx + c \end{aligned} \tag{5-7}$$

$$\begin{aligned} &y : height\ values\ of\ groove\ points \\ &a : determined\ median\ curvature \\ &y_1 : result\ of\ known\ values \end{aligned}$$

Figure 45 shows the differences between the first parabolic fit (in green) and the second parabolic fit with the median curvature (in violet) in the case of a dirty groove. It shows that, due to its fixed curvature, the second fit is able to find a good estimation of the actual buried groove.

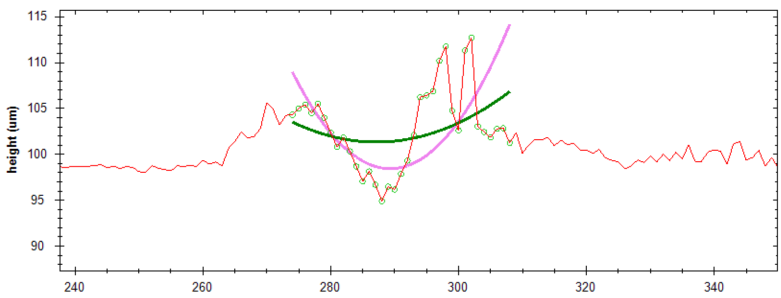

Figure 45: Comparison between 1st fit and median fit

The exact groove center is finally found at the minimum of the constraint fitted parabolic function, which is defined as follows.

$$groove\ center = minimum = -\frac{b}{2a} \tag{5-8}$$

5.4.5 Remove Outliers

During the constraint parabola fit with the median curvature, outlying points may disturb or falsify the placement of the curve, which would further lead to a wrong determined groove center.

In order to decrease or even suppress the impact of these outlying points, they are removed and corrected with better points during the fit. The followed procedure is illustrated by Figure 46, which shows that only one outlier is corrected at one time. The corrected point is then used for the calculation of a new fit before any other outlier is searched and replaced. The final fit is found if there are no more outliers determined to be corrected.

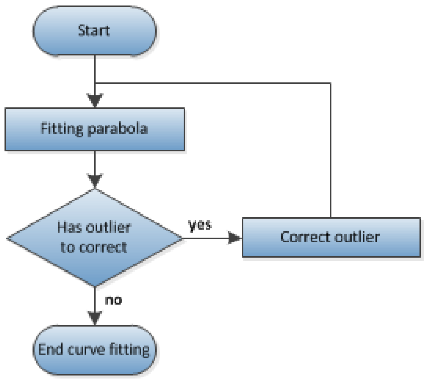

Figure 46: Outlier removal loop

Outlier determination

Three conditions have to be fulfilled in order to determine an outlier to be corrected.

1) Point exceeds the threshold distance
2) Maximum distance in the groove
3) Correction maximum not reached

The first condition determines whether a point is even regarded as outlier. Thereby, the distance between the point value and the function value from the fitted curve must exceed the threshold distance. The first condition can therefore be expressed as follows.

$$|p_i - y(i)| > threshold \tag{5-9}$$

$$p_i : point\ value$$
$$y(i) : function\ value$$

Since the first condition might be true for several points over a groove, the second condition demands that the only regarded point is the most disturbing one. Thereby, the outlier presenting the biggest difference compared to its function value is defined as the most disturbing one.

In order to fulfill the third condition, the maximum amount of allowed corrections per groove sample must not be reached.

$$corrections\ on\ current\ groove\ sample\ < MAX\ corrections \tag{5-10}$$

Outlier correction

If a point fulfills all the three conditions it is determined as an outlier that has to be corrected. This correction simply replaces the point value with the corresponding function value of the fitted curve. By doing so, the point is placed much closer to the other points of the groove and does therefore not disturb the following fits. Figure 47 shows the principle of the outlier correction where two outlier points are corrected and lead to the final curve fit in the 3rd transition.

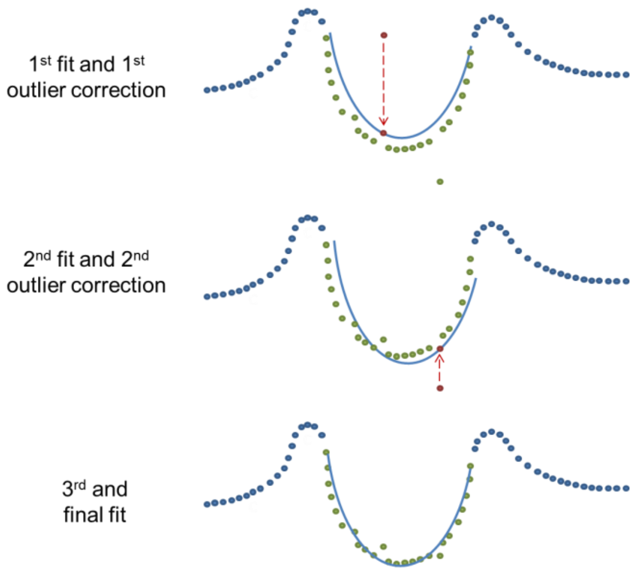

Figure 47: Principle of the outlier correction

Example

As an example of the implementation, Figure 48 shows a fitted parabola (in violet) and the two corrected outlier points (brown triangles). It is visible that the corrected points are much closer to the fitted curve and are consequently no longer disturbing. Since the maximal number of outliers to correct was two for that example, only the two most outlying points have been corrected.

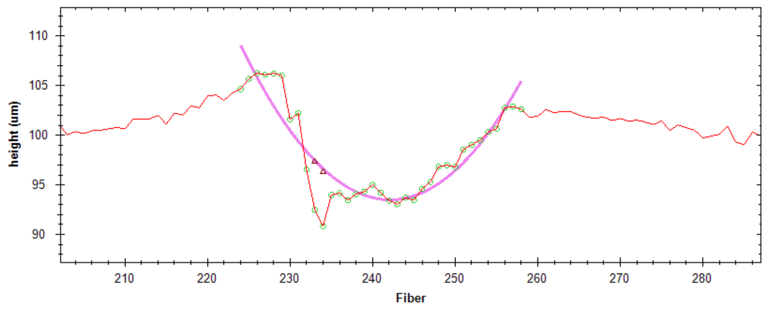

Figure 48: Example of corrected outlier points

5.4.6 Interpolation

Once the groove centers of all the groove samples are calculated, theoretically the needed information for the sound reconstruction is compiled. However, some of the determined groove centers are expected to be wrong, which can lead to additional noise or even clicks in the resulting sound file. In order to reduce or suppress such undesired effects, an interpolation in time has been introduced. The two main reasons for wrong groove centers are:

- Dirt or dust in the groove of the disc
- Big amount of bad points in the groove scan

Thereby, the big amount of bad points is mostly due to scanning issues or issues during the merge of several scanned revolutions.

Due to the need of a time interpolation for the aluminum discs, the class *TimeInterpolation* has been introduced into the program code. By now, this class is only used by the *Disc_QuadAlu* class but since the performed interpolation is not related to the recording type, it could also be used for other *Disc* or *Hardware* extensions. This utility for other classes is at the same time the reason for the existence of the *TimeInterpolation* class. Its structure is presented by the Figure 49

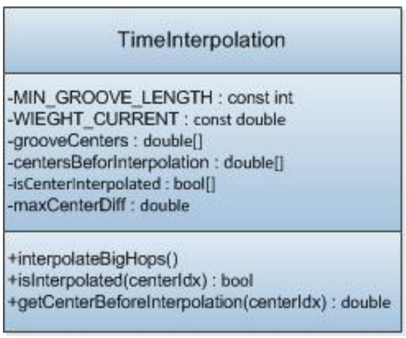

Figure 49: Class TimeInterpolation

Basically, the class *TimeInterpolation* operates in two steps; one defining which of the groove centers is wrong, the other correcting the wrong ones. Both are presented more detailed in the following subchapters.

Determining wrong centers

Instead of judging on the results of the groove center calculation in order to determine the wrong or problematic groove centers, the implemented interpolation uses only the position of the groove centers. In order to determine a bad groove center the position difference between two successive centers is compared. If the difference exceeds a threshold, the center position inducing the difference is considered to be bad. Figure 50 illustrates this procedure.

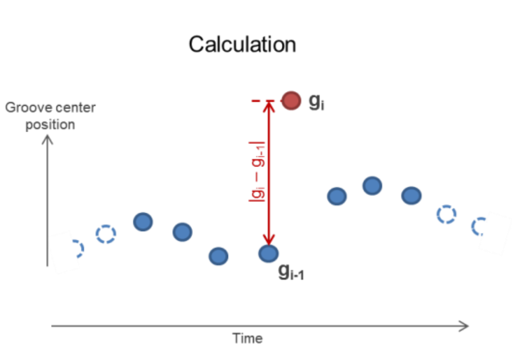

Figure 50: Determining wrong groove centers

This technique of finding bad groove centers can be used because the common sampling frequency for aluminum discs is 46.8 kHz. Thus, a high frequency component of 10 kHz would need about 5 samples for a period. Furthermore, it has to be considered that the high frequencies are much attenuated on aluminum discs [3], which entails only small amplitudes for fast groove changes.

Correcting wrong centers

The second task of the interpolation is to replace the bad groove centers with the information of its correct neighbors. The *TimeInterpolation* class does this in two steps.

- Mean of two neighbors
- Weighting by previous

A first step replaces wrong groove centers by the mean value between the previous groove center and the following one (Equation (5-11)). It is thereby not important whether the following point is also a bad groove center as this step only aims to get rid of the isolated bad centers and to decrease the difference between two groove centers.

$$g_i = \frac{g_{i-1} + g_{i+1}}{2} \tag{5-11}$$

g_i : *replaced groove center*
g_{i-1} : *previous groove center*
g_{i+1} : *following groove center*

Figure 51 illustrates the impact of the first step on an isolated and a non-isolated wrong groove center.

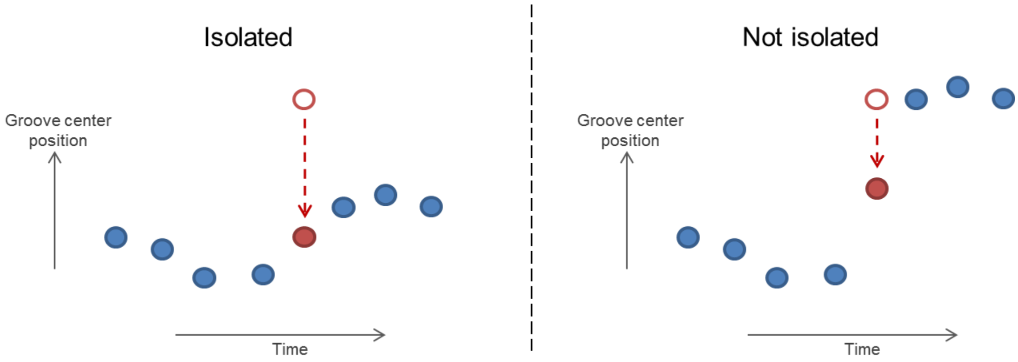

Figure 51: Principle of 1st interpolation

The first step implies that all the bad groove centers in the second step contain further bad centers. However, it is not known if there are only a few followed wrong centers or if there are many. The reason of this lack of knowledge is that the next correct center cannot be determined, which at the same time makes the use of a polynomial regression unreasonable. The goal however is not to find the next correct value but to reduce the click producing big differences between two groove centers. In order to do this, a bad groove center is corrected by weighting it with the previous center, as it is shown by Equation (5-12).

$$g_i = weight \cdot g_i + (1 - weight) \cdot g_{i-1} \tag{5-12}$$

g_i : $replaced\ groove\ center$
g_{i-1} : $previous\ groove\ center$

As an example, Figure 52 shows the result of the weighted interpolation used in the 2nd step. The used weighting of the wrong groove centers is thereby around 20%, which corresponds to the implemented weighting constant.

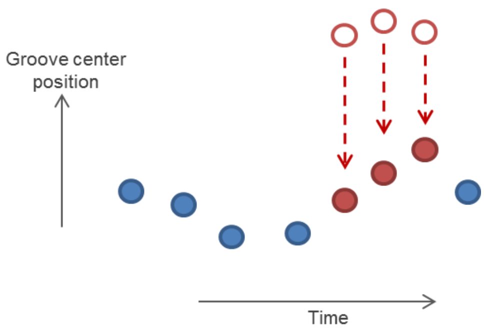

Figure 52: Principle of 2nd interpolation

This weighting is similar to a smoothing, but since it is only applied in the regions of wrong groove center it is not comparable to a smoothing filter on the resulting audio file.

5.4.7 GUI

In order to make the progress of the aluminum discs accessible for the user, so that he can modify calculation parameters or comprehend the performed process, several additional implementations have been added to the PRISM software. These GUI implementations can be classified in three domains, which are presented by the following subchapters.

Tab Quad-Alu & MenuItem MatchALU

Before the user processes any kind or scanned data he can choose the recording type as well as the algorithm to apply. Most of these algorithms provide the user with some changeable parameter values. Regardless of the recording type he can further decide about other independent parameters.

In order to maintain this initial procedure for the user, the new introduced aluminum processing is added as a new tab (Figure 53) among the other disc processing algorithms. This tab is mainly the link between the GUI and the *Disc_QuadAlu* class.

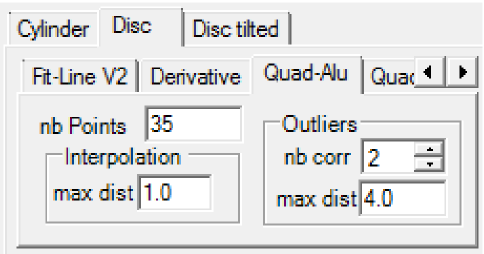

Figure 53: New tap Quad-Alu

The following table presents the parameter that can be modified in order to adapt the behavior of the algorithm.

Parameter	Default	Explanation
nb Points	*35*	*This parameter defines the expected groove width in number of points. It determines the amount of groove points that are going to be considered for the calculation.*
Interpolation max dist	*1.0*	*Defines the threshold that determines the maximal allowed variation between two successive groove centers. All variations above the threshold are interpolated in time.*
Outliers nb corr	*2*	*This parameter specifies the maximal number of outliers that may be corrected.*
Outliers max dist	*4.0*	*Similar to the max dist parameter of the interpolation. Allows setting the threshold for the distance of the outlying points. All points containing a bigger distance to the fitted parabola are considered as outlier.*

Beside the tab allowing adapting the processing algorithm, a menu item, shown by Figure 54, has been introduced that selects the specific match pass for aluminum discs.

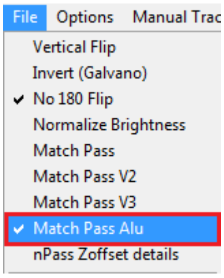

Figure 54: New added menu item

Although the processing algorithm of the *Disc_QuadAlu* class is independent of the used match pass algorithm, it is highly recommended to use the MatchALU algorithm for the aluminum discs. It has especially been developed for this disc type and therefore leads to better match results.

Display groove information

For reasons of debugging or just as a verification of the performed calculation of the algorithm, some checkboxes in PRISM allow adding information on the displayed cross section of the grooves. Most of them are not dependent on the disc or recording type and are identical for all. However, since the drawing is made by each recording type class, also the ones that are identical for all algorithms had to be implemented into the *Disc_QuadAlu* class. The checkboxes with their explanations are presented in the following table

Checkbox	Explanation
Draw Points	*Allows adding the actual measured points to the groove line.*
Vertical	*Instead of displaying the horizontal cross section of a disc, this checkbox allows displaying the vertical cross section.*
Interpolated points	*This checkbox is different for each algorithm. The idea is to display the points that have been interpolated during the processing.*
Draw lines	*This checkbox is different for each algorithm because every algorithm determines the groove center in another way. The idea is to show some information about the calculation so that the user is able to understand the groove center position.*
Center	*Displays the position of the calculated groove center.*
Brilliance	*Allows plotting the brilliance values over the depth values.*

The only checkboxes that are specifically related to the Quad-Alu algorithm are *Interpolated points* and *Draw lines.* When using the Quad-Alu algorithm, *Interpolated points* displays all points that have been corrected and the interpolated groove centers. The following table explains the symbols that are added when *Interpolated points* is checked.

Symbol	Explanation
Grey circle	*Shows the bad points that have been corrected during the match pass.*
Grey plus	*Shows the bad points that have been corrected after the match pass, already in the Quad-Alu algorithm*
Brown triangle	*Shows the corrected outliers points.*
Green line	*Indicates that a center has been time interpolated.*

Figure 55 shows an example of the added symbols.

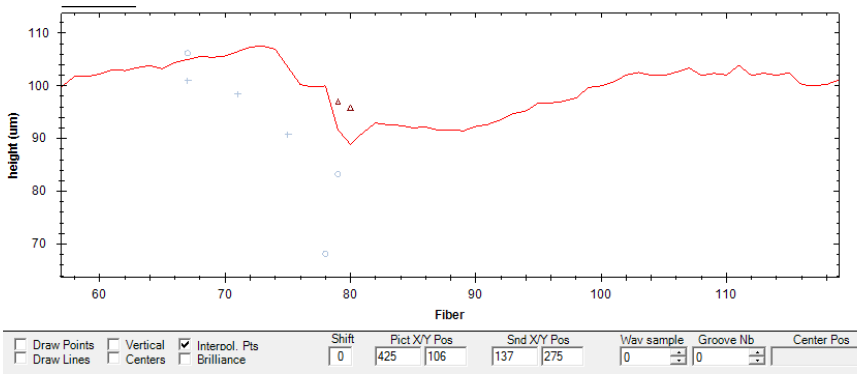

Figure 55: Checkbox Interpolated points

The second checkbox specific to the Quad-Alu algorithm is *Draw lines*. It allows the display of the points that are considered for the calculations in green and the resulting parabolic fit in violet. Figure 56 shows an example of the added information.

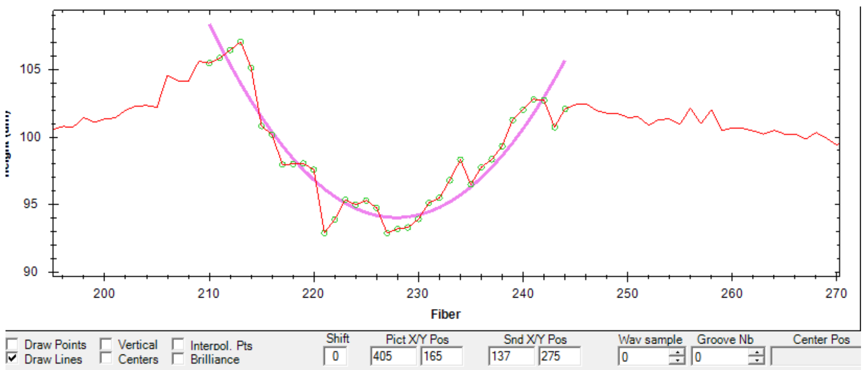

Figure 56: Checkbox Draw lines

Display groove or wave sample

Having information about the performed calculation due to the groove display allows getting a global view of the processing result. If however the resulting sound file contains noisy parts or clicks at specific moments, it is almost impossible to find the corresponding groove samples that cause the problem with the initial PRISM program.

In order to cover this demand, a tool has been implemented, that allows finding and displaying a groove sample by indicating the sample number of the wav file. However, since PRISM performs calculations on the groove sample numbers during the generation of the audio file, the groove sample number in PRISM does not directly correspond to the sample number in the wav file. Moreover, this calculation contains an irreversible rounding so that it is not possible to determine the groove sample number with a guaranteed exactitude. Therefore, a minor error of a few groove numbers has to be accepted.

If an audio file sample number is introduced, the tool directly indicates the corresponding groove sample number and the calculated groove center position apart from the fact that the chosen groove's cross section is displayed. Instead of searching for a sample number of the audio file it is also possible to display the cross section of a groove though by indicating its groove sample number.

In conclusion it can be said that the tool, which positioning is shown by Figure 57, allows the display of the cross section of a groove by indicating either the PRISM groove sample number or the audio file sample number.

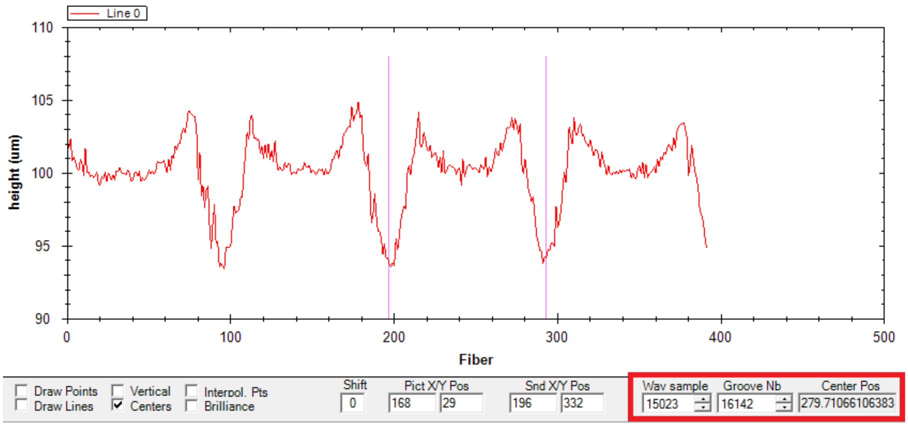

Figure 57: Debugging tool

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6 Tests & Evaluation

In order to evaluate the good functioning of the implementation and, consequently, the produced sound, five aluminum discs containing different characteristics are tested in more detail. Since the verification of the algorithm functioning has been done during the implementation, the tests of this chapter attempt to find the situations in which the algorithm works fine and where the problems and limitations are instead.

6.1 The five discs

In order to cover most of the differences in the groove shape and in the recording date, five discs have been chosen for more detailed tests. In this connection, the disc numbers are an indicator of the recording date (early recordings contain small numbers) and at the same time it is the only label on them. The following subchapters aim to present these discs by pointing out their particularities.

The parameters for the interpolation and for the outlier processing are always the same for the tests of this five discs. Only the number of points determining the groove has been adapted for each disc.

Parameter	Value
Interpolation maxdist	*1.0µm*
Outlier nb corr	*2*
Outlier max dist	*4.0µm*

6.1.1 Disc *68*

Disc number 68 is the oldest disc that has been provided for the analysis. This is the first reason why it has been chosen for the tests. Another reason is its particular groove shape, which contains large lobes on the side pointing to the outside of the disc. Figure 58 shows these unilateral lobes in a cross section of the scanned disc. In the figure it can further be seen that the groove sides and bottoms contain a lot of noise.

The parameter *nb Points* defining the number of groove points that are determined for the calculation has been set to 35 for this disc.

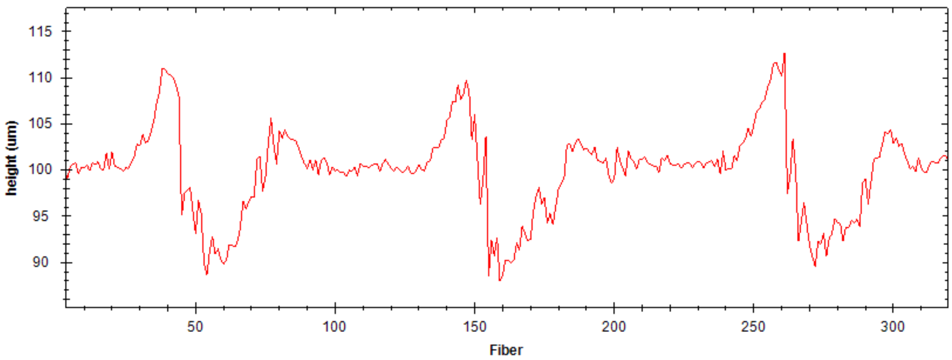

Figure 58: Groove shape of disc 68

6.1.2 Disc *2991*

The second disc that has been chosen for the tests is still one of the earlier recordings. The reason for the choice is its common groove shape. Therefore, it represents all the discs that contain a proper U-formed groove, which is about 10µm deep and has two side lobes of the same height and can be considered as the standard aluminum disc, which is shown by Figure 59.

Since the groove is very common, the most frequent number of groove points (*nb Points*), 35, is chosen as parameter for the algorithm.

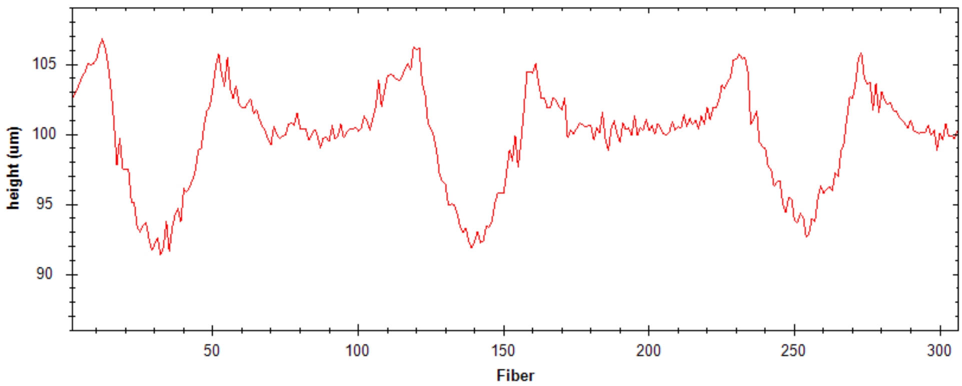

Figure 59: Groove shape of disc 2991

6.1.3 Disc *4147*

The disc 4147 contains similar to the disc 2991 rather well U-formed grooves. However, its particularity is the side lobes, which are quite big. An example is illustrated by the cross section of the scanned disc in Figure 60.

Due to the fact that the lobes on each side of the grooves are from a similar height, attempts are being made to use this additional information by setting the *nb Points* parameter to 43.

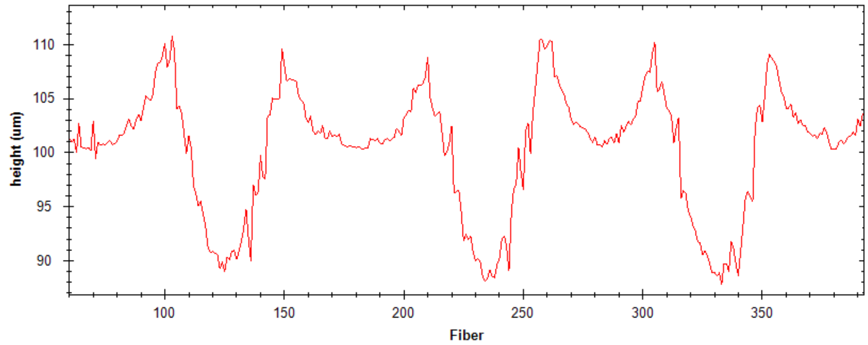

Figure 60: Groove shape of disc 4147

6.1.4 Disc *6765*

This disc number 6765, which is one of the newer recordings, has been selected for the tests, because it contains rather small groove depths. It is also one of the discs that have only small side lobes as is visible in Figure 61 that considers the height scale. Furthermore, the figure shows that the groove shape of this disc is almost V-formed and therefore theoretically less appropriate for the parabolic fit.

Even though the groove is small, the parameter determining the number of groove points is set to the common 35 points.

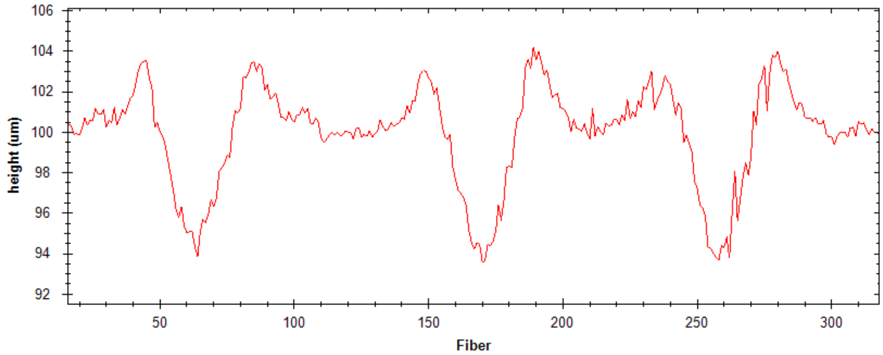

Figure 61: Groove shape of disc 6765

6.1.5 Disc *UntitledDR*

The last selected disc is the only one that contains no number and therefore cannot be classified chronologically. Compared to all other provided disc, it contains very difficult groove characteristics; the groove is very deep and the lobes are very high. Furthermore, the disc possesses an almost rectangular groove bottom. Figure 62 shows these unusual characteristics.

Due to the fact that the groove is deeper, 49 points are set as parameter *nb Points.*

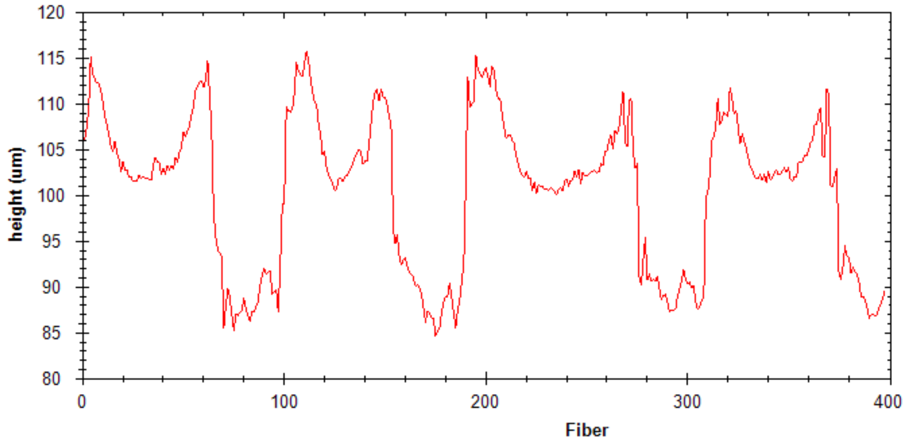

Figure 62: Groove shape of disc UntitledDR

6.2 Results

After having selected the five discs, they have been processed, so that the results of each of them can be presented and discussed in this subchapter.

6.2.1 Disc *68*

As mentioned before, this is the earliest aluminum disc recording that has been provided by Harvard University. Due to the fact that there is also a stylus version of this disc, the reconstructed sound is compared to it after presenting the reconstructed sound.

Reconstructed sound

Figure 63 presents a part of the unmodified waveform that is obtained after the processing of the scanned data by the new implemented algorithm. It shows a high amount of noise, so that the sound information is almost invisible. Furthermore, there are some few, not very disturbing clicks in the wave file.

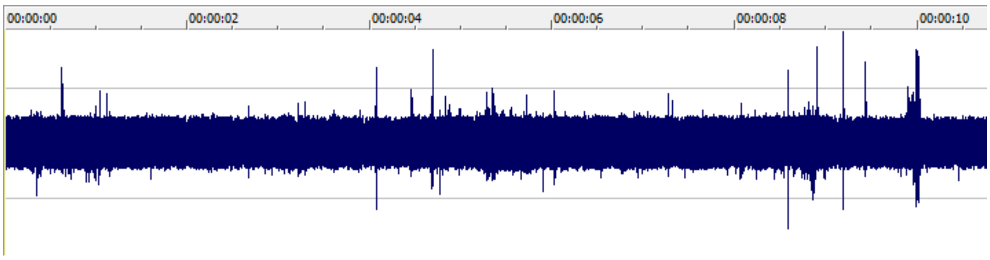

Figure 63: Resulting waveform of disc 68

By observing the reconstructed sound in frequency domain (presented by Figure 64), we can see why the sound information is not visible in the waveform; there is a lot of high frequency noise containing the same or even higher level than the audio content in the lower frequencies. Figure 64 further shows that the sound information is well present between 200 Hz and 2 kHz.

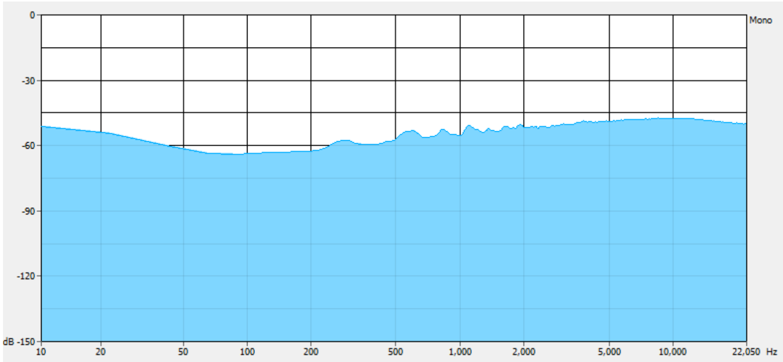

Figure 64: Spectrum of disc 68

Although the waveform is not very clean, the sound is audible. However, the high content of noise is disturbing the hearing.

Comparison with stylus version

As a comparison to the 3D result, Figure 65 shows the waveform created with a stylus playback. Here, the sound information is clearly better visible.

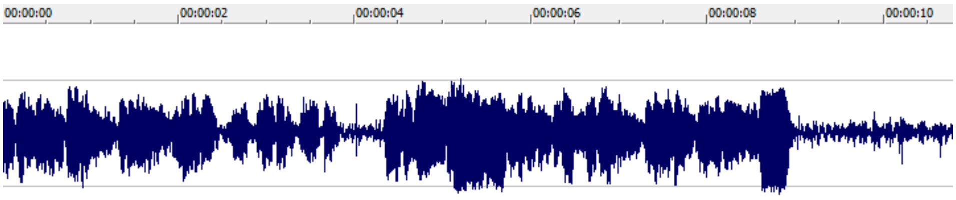

Figure 65: Stylus waveform of disc 68

Figure 66 shows the result in the frequency domain. The 3D version is presented in light blue and the stylus version in violet. It can be seen that the stylus version contains a much less amount of high frequency; it contains more low frequencies. However, the actual sound information in the middle of the spectrum is similar in both versions showing that the algorithm produced a lot of high frequency, which could be due to big variation between the calculated groove centers. Since the stylus playback of the disc is operating like a low-pass filtering, this filtering effect could also be introduced for the 3D result, so that the high frequency noise would be less important and, thus, less disturbing.

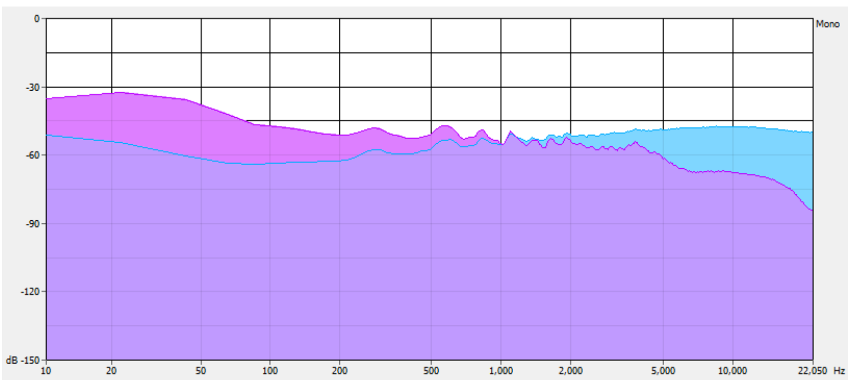

Figure 66: Comparison between stylus and 3D version of disc 68

6.2.2 Disc *2991*

Disc 2991 was selected for the tests because of its standard groove structure. Figure 67 shows an extract of the resulting waveform after processing without any filtering. Compared to the waveform of disc 68, the sound structure is much more visible for that disc. However, it seems that the clicks are slightly more frequent.

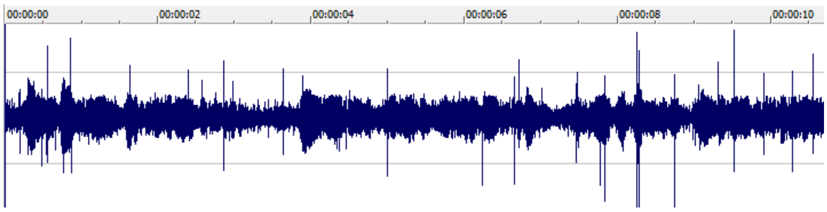

Figure 67: Resulting waveform of disc 2991

The corresponding spectrum, presented by Figure 68, shows the reason of the better visible sound information in the waveform; most of the audio content is at a higher level than the high frequency noise. Even if the result is better compared to disc 68, it would still be worth applying a low-pass filter in order to reduce the high frequencies and, as a result, reduce the amount of noise.

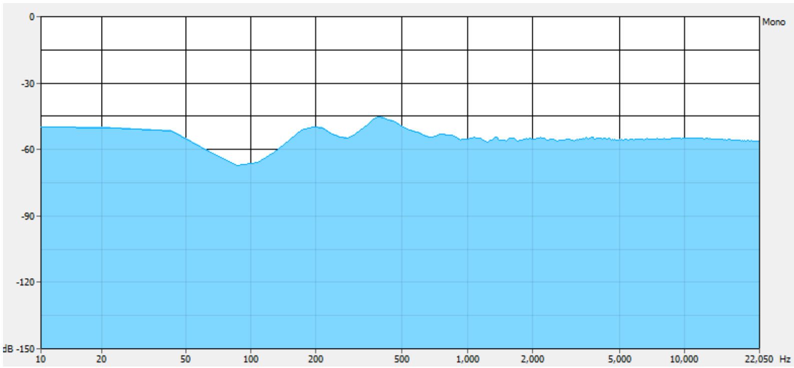

Figure 68: Spectrum of disc 2991

What has been observed by analyzing the resulting audio file in time and frequency domain could also be confirmed in the acoustic verification; the noise is less disturbing than for disc 68. The acoustic verification further explained the reason of the invisibility of audio components on the spectrum: the reconstructed part only contains speech.

6.2.3 Disc *4147*

For this disc, which has been selected for its high side lobes, a stylus version and a result from the IRENE system are available. Therefore, after presenting the results of the disc, the comparisons to the two other provided sound files are made.

Reconstructed sound

The resulting waveform of this disc seems to be something in between the waveforms of the discs 68 and 2991. Even though the audio content is more or less visible, the waveform seems to contain a not unimportant amount of noise. Furthermore, a certain amount of clicks is again present. Figure 69 shows a part of the created sound file.

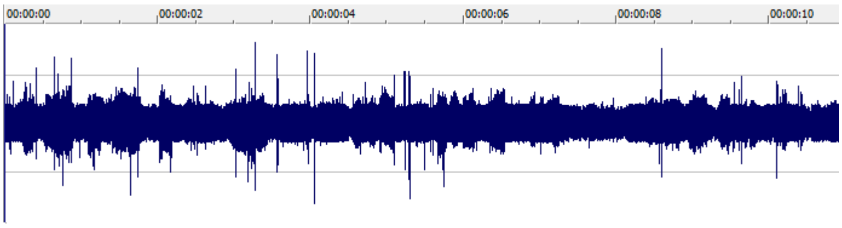

Figure 69: Resulting waveform of disc 4147

Figure 70 presents the spectrum corresponding to the waveform showing that the waveform contains visible audio components up to 5 kHz, which surmount the noise. The effective amount of noise seems therefore less important than supposed with waveform.

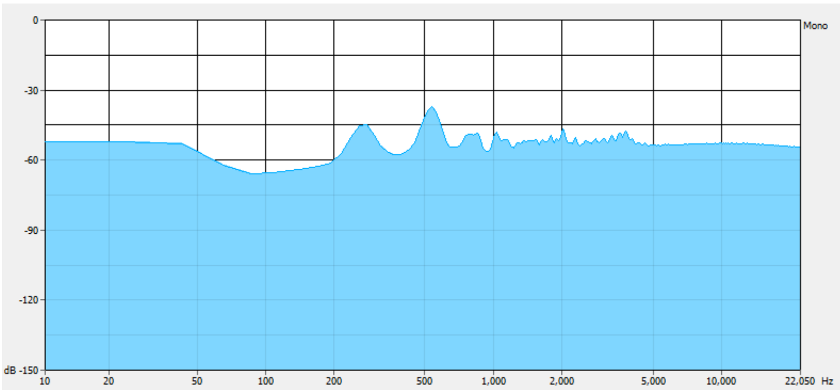

Figure 70: Spectrum of disc 4147

By listening to the created audio file it can be noticed that the acoustic result is similar to the quality of the disc 2991.

Comparison with stylus version

Similar to the comparison with the stylus version of disc 68, the stylus waveform is again less noisy, as is visible in Figure 71.

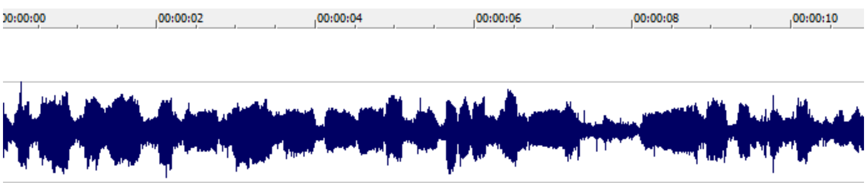

Figure 71: Stylus waveform of disc 4147

The observation of the disc's spectrum in Figure 72 has revealed that the spectrum does only differ at the high frequencies. The stylus spectrum in violet is lower in the high frequencies than the one of the 3D (light blue). However, the differences in these high frequencies are not that significant because the audio seems only to be present until about 5 kHz. Therefore, the frequencies above could be filtered. More important, however, is the fact that the frequency components between 2 kHz and 5 kHz are sharper (top to bottom is bigger) with the stylus version. This is an indication for less noise in those components.

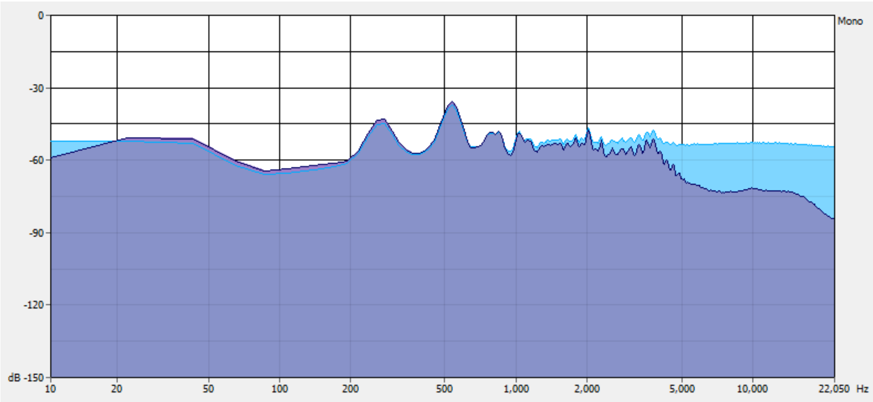

Figure 72: Comparison between stylus and 3D version of disc 4147

Comparison with IRENE version

As a comparison between the resulting audio files of the 2D and 3D system, shows both spectrums. The violet curve corresponds to the 3D result and the orange curve to the 2D result. Since the part of the disc is not exactly the same as for the previous comparison with the stylus, the spectrum is slightly different.

It can be seen that, contrary to the comparison with the stylus, the 3D result possesses the sharper and, thus, less noisy spectrum. This time, differences are recognizable even in the low frequencies.

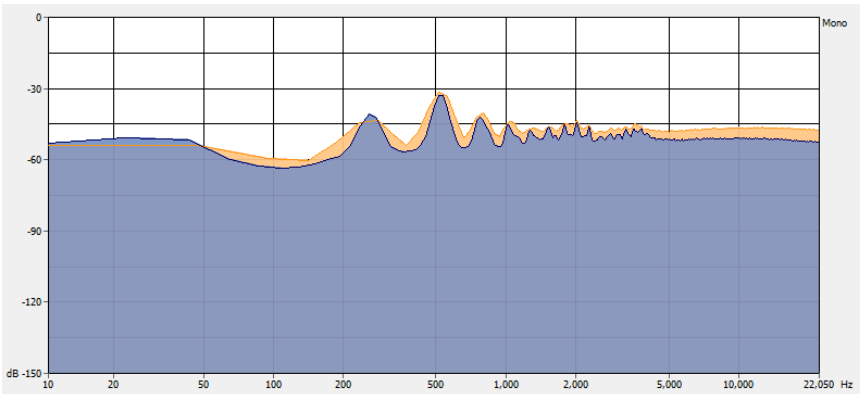

Figure 73: Comparison between IRENE and 3D version of disc 4147

6.2.4 Disc *6765*

The disc 6765 is the newest recording that has been tested. Figure 74 presents the resulting waveform, on which only few clicks are visible. At the same time, the audio is clearly recognizable which indicates less noise.

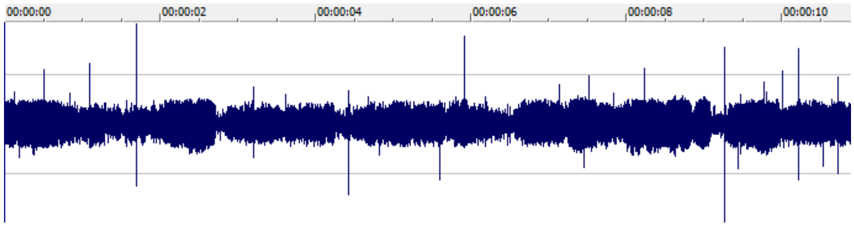

Figure 74: Resulting waveform of disc 6765

The spectrum, shown by Figure 75, is similar to the one of the disc 4147. The high frequency noise is not very big compared to the audio components between 200 Hz and 5 kHz. This explains why the sound is well recognizable in the wave file.

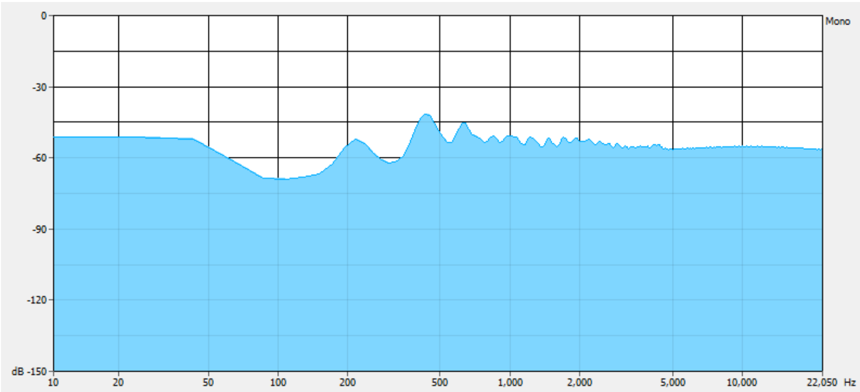

Figure 75: Spectrum of disc 6765

The acoustic verification confirms what has been observed in the waveform and in the spectrum; the sound is well audible. However, a certain amount of noise in the audible range is still audible.

6.2.5 Disc *UntitledDR*

Because of its much deeper groove and its rectangular groove shape, the disc *UntitledDR* is very different compared to all the other provided aluminum discs. The existing audio file that has been created with the 2D technique allows comparing the result of the new algorithm.

Reconstructed sound

Even though the sound structure is relatively recognizable, there are a lot of clicks in the waveform shown by Figure 76. Here, most of the clicks and unclean parts occur in the unquiet regions.

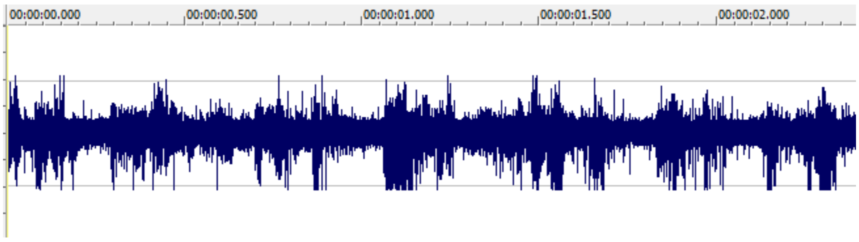

Figure 76: Resulting waveform of disc UntitledDR

The corresponding spectrum (Figure 77) shows a little bump around 5 kHz that had already been observed for the rather noisy disc 68. It might cover some audio components. The audio components are only visible until 1.5 kHz, but may go higher in reality.

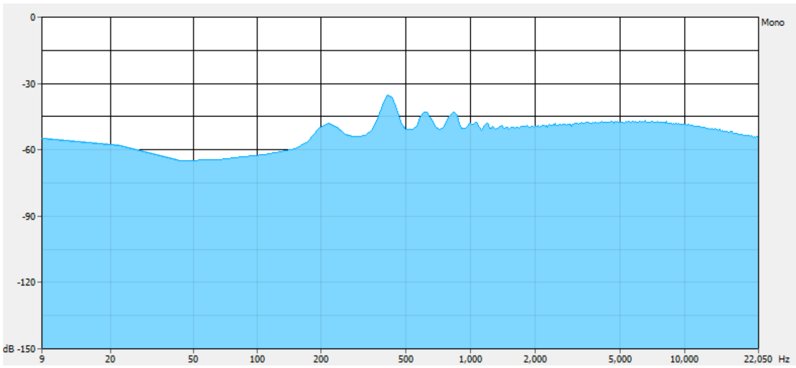

Figure 77: Spectrum of disc UntitledDR

Comparison with IRENE version

As a comparison to the 3D waveform, Figure 78 shows the obtained result from the 2D system. The sound structure is more difficult to determine, but at the same time the importance of the clicks is lower.

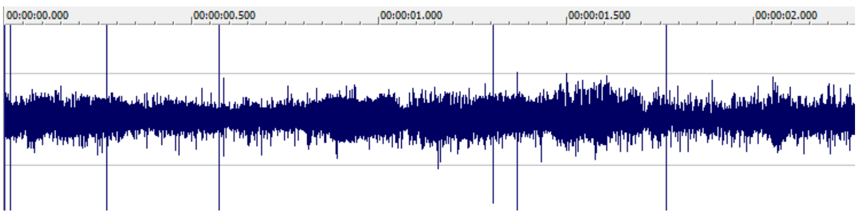

Figure 78: IRENE waveform of disc UntitledDR

Figure 79 presents the compared spectrum: the orange curve corresponds to the 2D version and the violet curve to the 3D version. In contrast to the comparison for the disc 4147, where the 3D spectrum was sharpener (larger peak to valley distance), the spectrum of the disc

UntitledDR seems to contain sharper frequency components for the 2D audio file. Moreover, the high frequency noise is lower for the 2D generated sound.

The reason for the great result with the 2D technique is most certainly the unusual flat groove bottom of this disc.

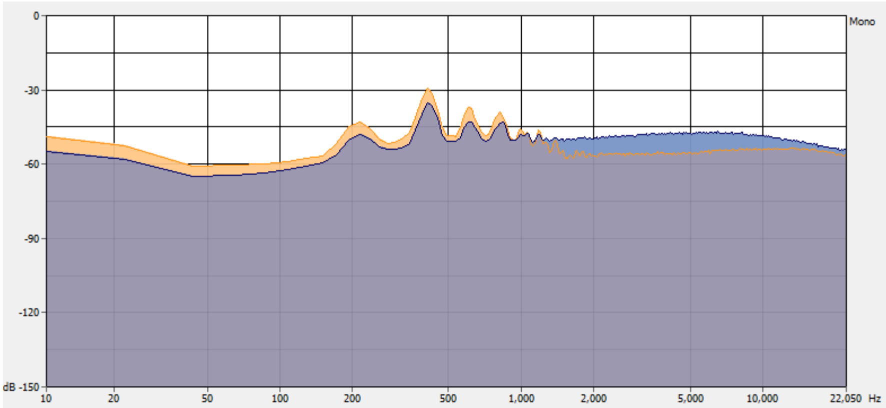

Figure 79: Comparison between IRENE and 3D version of disc UntitledDR

6.3 Result evaluation

By analyzing the test results, some important points can be said about the implemented algorithm and its comportment with aluminum discs from various characteristics. The following subchapters present and discuss these points.

6.3.1 Sound quality

During the tests of the five selected and all the additionally processed aluminum discs, one important common feature could be observed; all the discs data that has been processed with the *Qual-Alu* algorithm lead to an audible audio file. As it can be seen in the test results, some are of better quality than others, but none of the reconstructed audio files has been inaudible due to a problematic case in which the algorithm does not respond.

It could further be determined that common grooves containing similar side lobes on both groove sides and a U-formed shape are very likely to be processed and often lead to a good result. One reason for this is supposed to be the appropriate shape for the parabolic fit. An additional point that can be considered is when both side lobes are similar, which may be another reason for the good result.

The test also showed that the stylus quality is not reached yet. The biggest difference is contained in the high frequencies. Since the stylus is acting as low-pass filter during the playback, filtering the reconstructed audio file can do the same. Therefore, this difference is not very disturbing. More important is that the stylus result seems to contain less noise in the audible range, which simply cannot be filtered.

A further interesting result was the good responding of the disc *UntitledDR* to the 2D processing. This shows that the 2D system might be a solution for the very particular aluminum discs in the Milman Parry collection, which contain a steep transition between groove side and groove bottom.

6.3.2 Bad points

By analyzing the scans of the disc that led to less good test results it could be seen that there is often a correlation with the amount of bad points in the scanned data. In this case, the bad points are not very disturbing for the fit of the parabola. They much more disturb the determination of the groove points, which may have a big impact on the result. Figure 80 shows an example of such a situation. The bad points at the left side of the groove bottom entail that the found local minimum is not in the center of the groove bottom. As a consequence, too many points are considered as groove points on the left side and not enough on the right side. The figure shows also that it is rather the position of a bad point that matters than its distance to the good points.

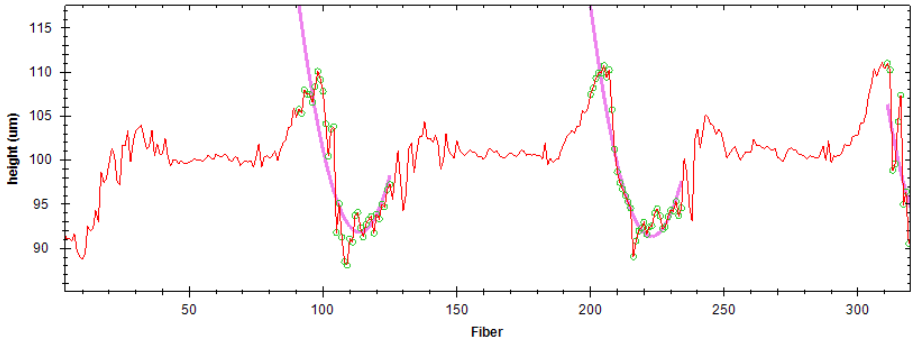

Figure 80: Wrong determined groove point in disc 68

6.3.3 Amplitude & Noise

Another observation that can be made from the test results is that the amount of noise in a reconstructed audio file is almost always related to the amplitude (horizontal movement) of the grooves. The bigger the amplitude on a disc is, the lower the noise seems to be. This correlation makes sense if the generated noise originates from the imprecision of the groove center determination.

Among the tested and the additionally processed discs it could be observed that the earlier recordings more likely tend to be noisy than the latter ones. By analyzing the discs, it has been found out that the amplitudes of the discs also correspond to this pattern. This means that there is a time-dependence on the discs. However, this dependence is not visible in the groove shape but in the amplitude of the grooves.

7 Remarks & Problems

In every project, at some point, problems are encountered or solutions are not that convincing as desired. In order to prevent future projects from struggling with the same problems or trying out the same solutions, this chapter aims to present the most important encountered problems and the unsuccessful approaches of this project.

7.1 Unsuccessful approaches

In order to find satisfying results for the processing of aluminum discs, many variations of the different algorithm steps were tested and verified. The best ones have been further developed and implemented in the final version, but there were also promising approaches that appeared to be less successful than expected. The most important among them are presented in this subchapter.

7.1.1 Groove points through fitting

One of the unsuccessful approaches is related to the algorithm step, in which the groove points are determined.

Instead of searching for a local minimum over a given range, it has been tried to determine the groove points by calculating a polynomial fit for every point in the range. The polynomial function containing the least deviation to the points is found to fit the best and defines the groove points.

Figure 81 shows the principle of this approach by illustrating the 1st and 6th fit.

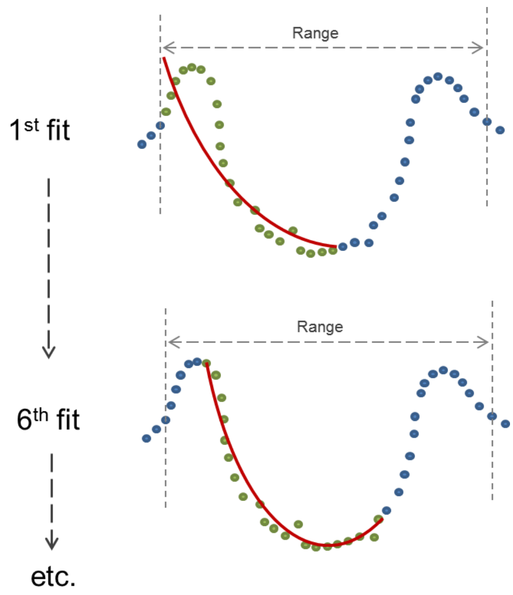

Figure 81: Principle of groove points determination by fit

Two different variations of this approach were tested:

- As replacement of the implemented local minimum algorithm
- As supplement to the implemented local minimum algorithm

Both results were not satisfying because the calculation of several polynomial regressions per groove sample and their groove sample is very time consuming. This would not be very important if the result was better, which however has not been the case.

By using the approach as a supplement to the implemented algorithm, the fit was thought to correct the found local minimum slightly. Because not the entire defined range has to be processed, the calculation is a little bit less time consuming, but the desired improvement is not achieved. The result is even worse than without the fit approach as the profit of the weighting in the implemented algorithm is lost through the modifications on the local minimum point.

7.1.2 Restricted local minimum

Similar to the first unsuccessful approach, this one is also related to the determination of the groove points which are used for the further calculations.

The approach aims to refer the search of the local minimum point more to the previous calculated local minima. Instead of searching to apply the local minimum algorithm on the entire range every time the range is restricted to the previous found local minimum. An example of a restricted range would be the previous local minimum ±5 points on each side.

This idea would on one hand be very efficient and on the other hand would take into account the fact that the maximal groove movement between two samples is limited. However, the result is very bad because there is no rescue for lost local minima. If the local minimum is on the groove top once it is almost impossible that it gets back into the groove because the lobes are usually higher than the top. Since the aluminum discs contain a considerable amount of dirt or bad points in the scanned data that can cause the local minimum to get lost, this approach is not satisfying.

7.1.3 Interpolation trough calculation judgment

Another important unsuccessful approach has been made for interpolation. Instead of determining the wrong calculated groove centers by comparing them with the previous ones, this approaches determined them on the basis of the calculations during the processing. If one of the following conditions had been fulfilled, the groove center would have been marked to be bad.

- First fitted parabola has negative curvature
- First fitted parabola is very steep or almost flat
- Function minimum of first fitted parabola is not in the groove
- More than 40% of the groove points are outliers

In theory, these are the most obvious indications for an unusual groove. The practice showed however that only a few amount of the actual bad groove center positions could be detected in this way. Since only a little percentage of the actual problems is found, it does not matter if the correction is made directly on groove centers or after derivation on the sound samples.

7.2 Readout parameter

The readout is a parameter of the LabVIEW scanning program. It defines how many times per revolution the buffer of the XPS system should be read. Due to the fact that the aluminum discs have to be turned faster than other disc types, this parameter had to be reduced from a common value of 1000 to 10 (or even 1). The problem with this is that without reducing the value, the system was not able to take the 1000 readouts during one revolution. The 36000 samples were therefore not acquired over one revolution but maybe over one and a quarter or even one and a half revolution. Due to this, some information was left and other was redundant.

In cases of slight errors, this might not even be noticed in the resulting audio file, but in cases of great errors an echo in the audio file can be the consequence. The fact that the error can change from revolution to revolution makes it almost impossible to solve the problem. This independence of the error is further very annoying when performing a multiple pass scan, as every pass can contain the data of a different moment in the revolution. This can lead to almost unrecognizable grooves, as shown by Figure 82.

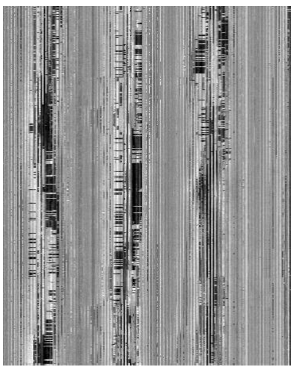

Figure 82: Effect of wrong readout value

To solve this problem, the lightest solution has been chosen; the readout parameter value has been lowered to 10. However, since scanning program uses the readouts not only to store the acquired data but also to display the scanned groove constantly, the lower readout is interrupting the display. With a readout value of 10, the data is read out the buffer 10 times per revolution and, thus, the display can merely be updated 10 times per revolution.

7.3 32bit vs. 64bit

Recently, a 64bit driver for the XPS system is available. This now allows acquiring and processing the data with the more powerful 64bit computer in the laboratory. Before, only the processing could be made with the 64bit machine and the acquisition had to be made with the 32bit computer.

However, this acquisition with the 64bit machine has not been as satisfying as expected, so that in the end the disc acquisition with LabVIEW was again run on the 32bit computer. The problem was encountered while struggling with the difficulties related to the readout value. Even though the readout value was 10 or even 1, small time shifts between the passes could still be observed. Since this effect did not occur with the 32bit computer, it is supposed to be related to the different driver. For this reason, the 32bit machine has been chosen for all the subsequent scans and tests.

8 Further steps

At the end of this project, different points remain that would be worth investing in the future in order to get an additional value in several parts of the project. This chapter aims to present these further steps by subdividing them into the acquisition and the processing part, which are related to other software and other programming languages.

8.1 Acquisition part

Since the acquisition of aluminum discs do not differs that much from the acquisition of other disc types, the points that would be improved in the future do mostly concern the 3-dimsional scanning technique and not necessarily the scan of aluminum discs.

8.1.1 Continuous acquisition

As calculations in chapter 0 have shown, time is an important factor for the 3D scanning, especially when the amount of discs that might be scanned is around 3000, as is also the case with the aluminum disc from the Milman Parry collection. Therefore, it would be desirable for the scan duration to be lowered in any way.

An idea would be to scan the disc in one piece as it is done for the 2D scan instead of turning the turntable back to position zero after each revolution. This may increase the amount of acquired data by a certain percentage because of the useless data during the inward x-shift. On the contrary, no more time would be lost for the time-consuming backward rotation, which almost corresponds to 30% percent of the scanning time.

8.1.2 Automatic tracking setup

Another investigation on the acquisition might be done for the starting procedure. By now, the laser tracking requires a setup that involves several steps, in which the user has to do measurements as well as parameter adaptions and adjustment before the disc can be scanned. Since these steps demand certain knowledge of the system and its functionality, it may not be ideal for an inexperienced person. Furthermore, the setup takes time and also experienced people easily make errors while setting up all the needed parameters.

A solution for this inconvenient setup would be to automate the entire laser tracking setup so that the discs can directly be scanned without any preparation or start-up procedure.

Especially if it was decided to scan the entire Milman Parry disc collection, it would be worth investing a significant amount of time to facilitate the setup before scanning, so that even inexperienced users are able to scan the aluminum discs.

8.1.3 Determine very deep points

Some of the disc scans contain very deep points that are more than twice as deep as the groove itself. Although some bad point correction is done during the processing, not all of the bad points are identified so that a few may still disturb the groove center calculations.

Due to the fact that these very deep points are often placed at the sides of the groove bottom, it might be that their reason is related to a damaged embossing tool. The damage created by the tool might then disturb the light so that it comes to a specular reflection.

In a further step it would be worth investigating on this effect so that the actual cause of these deep points can be found.

8.2 Processing part

In contrast to the acquisition part, the processing part is completely different for aluminum disc compared to other cut disc types or other recording types. Therefore, the here presented ideas for the future only concern the algorithm for the processing of aluminum discs.

8.2.1 Groove tracking

Before any calculations on the aluminum grooves can be performed, an estimation of the groove position is needed. By now, this so-called groove tracking is made by an existing technique in PRISM; the *Track Depth* method. This tracking method is used because it leads to the best results compared to the other methods (*Track Middle* and *Track Fourier*). Although *Track Depth* is the best working groove tracking, it is not able to track all the grooves of the aluminum discs correctly because it was not designed for the specific groove characteristics of the aluminum disc.

However, since the PRISM program also allows tracking the grooves manually, the incorrect found groove positions can be corrected. Therefore, the user has to follow the groove graphically on an image, which is time-consuming and very inconvenient if the loaded data concerns more than about 5 revolutions.

In order to improve the first groove estimation, a specific groove tracking algorithm for aluminum discs might be developed in a next step whereby he undesired and time-consuming manual tracking could be avoided.

8.2.2 Bad point detection

The disc scans contain a lot of bad points that are especially disturbing for the determination of the groove points because wrong determined groove points may falsify the further groove center calculations completely.

The current algorithm corrects a big amount of these bad points but there are still some left during the calculations. Therefore, it would be useful to improve the bad point detection and correction.

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9 Conclusion

The starting situation of this diploma work at the Lawrence Berkeley National Laboratory was given by the 26 provided aluminum discs out of the historical Milman Parry collection. The main aim of the project was to introduce this very specific disc type into the existing 3 dimensional acquiring and processing system in order to evaluate whether the scan of these disc would be a reasonable solution for the digitization, and therefore to preserve these unique recordings for the future.

This main objective has been divided into different smaller objectives, which are considered to be achieved since all the stages described in those objectives could be processed. Small modifications on the scanning software as well as the determination of the most appropriate parameters now allow acquiring the data of the aluminum disc in a good quality. At the same time, the acquired data can be processed by a new algorithm that has specifically been developed for the aluminum discs.

At the term of this project, after all the investigations, the insights and the results, it is now possible to make a more realistic feasibility estimation regarding the scan of the entire Milman Parry collection. Three points are thereby important:

- Scan duration
- Acoustic result
- Usability

The project has shown that the scans of aluminum discs are possible with the existing 3D acquiring system. A big problem however is the time that is needed to scan an entire disc. For the scan of about 3000 discs, it would therefore be worth overthinking the scanning principle. Furthermore, the tests have shown that the result is not comparable good for all the discs. Especially when the amplitude of the recording is weak or the quality of the scan is less good, the noise is much more audible. Some improvements on the robustness of the algorithm would be needed in order to equal good acoustic results for all discs in the collection. A very important point for an eventual scan of the about 3000 aluminum discs is the usability. By now, the acquisition software as well as the processing software are designed for several different recording types. This entails a large amount of parameters that can be changed, but have to be known. To simplify the work of a possible employee scanning the collection, a specific and user-friendly program should be developed for the acquiring and the processing. By simplifying the steps toward the audio file, it would further be possible to have the scans done by lower-educated employees or students. This would on one side lower the cost and render the scan duration less important.

All in all, this project has pointed out the difficulties and possibilities of the 3D scan of aluminum discs. It has also shown that the scan and sound reconstruction by 3D scanning is possible and is a promising way to digitize the unique recordings of the Milman Parry collection.

From a personal aspect, this project has been very interesting and informative for many reasons. First, the optical sound reconstruction is a fascinating field, especially when the concerned recordings are old, unique and contain important information. Furthermore, this project involved, from placing the disc on the turntable to evaluating the resulting audio file, all the steps of the sound reconstruction. This allowed seeing all the steps, the principles and the difficulties related with the 3D technique.

However, this involvement with all the reconstruction stages has also had its difficulties. All principles had to be understood so that modifications and new implementations could be added to them. In the case of the acquisition, the difficulty was related to the graphical programming language LabVIEW, which differs a lot from other languages such as JAVA or C. In the processing part the difficulty was related to the lack of a complete documentation and of comments in the code. These difficulties however helped to better understand the entire principle of the system.

All in all, this project at the Lawrence Berkeley National Laboratory was a great experience that on one hand allowed seeing another surrounding and on the other hand contributing to a big venture.

The author

Alain Benninger

10 Glossary

Word	Description
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench. Platform and environment for a visual programming language.
IRENE	Name of the 2D system that allows reconstructing sound from discs by using their reflectivity.
RENE	Name of the processing software of the 2D system.
PRISM	Name of the processing software of the 3D system.
Tracking (acquisition)	Following the disc surface in order to stay in focus even in the case of unevenness.
Tracking (groove)	First groove position estimation that is used for further calculations.
Fiber (light)	One light point of the 3D camera. There is a line of 180 of them in the used camera. Each one can measure a depth and an intensity value.
x-motor	Motor that moves the disc from the border to the center.
z-motor	Motor that adjusts the height of the camera.
n-Pass	Number of revolutions scanning the same grooves. A small shift between them allows getting a higher resolution.
rpm	Revolutions Per Minute.
Sample disc	One of the 26 aluminum discs that have been provided out of the about 3000 in the Milman Parry collection.
GUI	Graphical User Interface.

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11 References

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Appendices

DVD folder structure

- audio_files_from_tests
  - Disc68
  - Disc2991
  - Disc4147
  - Disc6765
  - discUntitledDR
- flyer
- functional_specification
- groove_samples
- howto_scann_aluminum
- intermediate_presentations
- LabVIEW_code
- matlab_code_for_tests
- minutes
- PRISM_code
- project_description
- weekly_reports
- working_journal