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# A Framework for Studying the Physical Degradation Characteristics of DVDs and Their Relationship to Digital Errors

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# ABSTRACT

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The methods used to store data on DVD-R discs have been proven to work over the last 15 years. However, there has been a growing concern that these discs will be outlasted by the paper records they were meant to replace. The data on a DVD-R is stored as optical contrasts which have the potential to be misread and even damaged. This damage may occur either on the surface or internally to the disc, especially on the recording layer itself. The literature is saturated with studies attempting to determine the time period in which discs may fail and what the general signs of the degradation are, but almost all fail to determine the fundamental causes of DVD degradation. In particular, the exact connection between the physical state of the disc and its digital errors is undetermined. This study undertook to develop a framework to study and understand this relationship. The study also consisted of a characterization validation experiment involving several brands of DVD-Rs. The framework constructed during the course of the research included several tools. Due to the lack of an existing tool able to aggregate the gathered data, a specialized software program, called SectorDraw, was developed. In the course of this study, this software tool was validated. Additionally, it was discovered that physical defects should be evaluated and characterized by using a process of visual inspection, microscope examination, and measurements. Although not all relationships between physical defects and digital errors were explored, the study established the fact that defects can directly cause bursts of digital errors. This indicated that there was a connection between physical defects and digital errors. It was also found that physical defects developed over time after treatments of artificial aging. The developed framework was established as viable for future research to study specific relationships between physical defects and digital errors.

Keywords: Brian Saville, DVD, optical discs, degradation, framework, SectorDraw, Barry Lunt, Millenniata, Dr. Schwab

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# 1 INTRODUCTION

Digital Versatile Discs, more commonly known as DVDs, have been in production for almost 15 years. As Compact Discs (or CDs) before them, the original format was extended to allow for recordable discs, known as DVD-Rs, to be manufactured in 1997 (Worthington 2006). Compared to the tried and true CDs they replaced, these discs had almost seven times the capacity, yet were comprised of similar materials, and worked on similar principles. It is no wonder that within a matter of years, they became a primary method of digital data storage. However, researchers became increasingly concerned with the alarming degradation of data stored on optical discs. It was discovered that even though the format seemed the archivists dream, DVD-Rs would be outlasted by the paper records they were meant to replace even if they were stored on shelves in controlled environments (Talbot 2005).

Data on an optical disc is stored as optical contrasts. Features on the disc either reflect, scatter, or absorb the light during the read process, and these differences are used to decode the original data stored on the discs. The process of reading an analog signal from the disc is often where data has the potential to be misread, lost, or damaged. The process is susceptible to errors, due to the degradation of the disc and artifacts that create interference such as objects on the disc's surface or within the disc's layers. While this degradation and its general effect on the deterioration of the data have been documented in literature, there is a lack of a model available to study this exact connection. This study attempted to bridge this gap by developing a framework for studying the physical causes of digital errors on optical discs.

## 1.1 Framework

While much has been completed to study the lifetime estimates of optical discs and their failure mechanisms (Slattery, et al. 2004) (Shahani, Manns and Youket n.d.) (Iraci 2005) (Svrcek n.d.), it is unknown exactly which combinations of mechanisms actually lead to unrecoverable data. Additionally, the nature of what data failure truly means physically is vague and almost completely undocumented. The condition of an optical disc can be measured by looking at the difficult-to-recover and unrecoverable data on the disc, or, in other words, by measuring digital errors with appropriate analysis equipment. These digital errors, which are assessed by reading the disc optically with a laser, have a physical foundation in the disc itself. Very little work has been done or found researching these physical characteristics, which are assumed to be manifested mainly by defects in or on the disc. In this study, a defect is defined as any physical manifestation on a disc that creates errors during the reading process.

It is also well established that as a disc ages, the digital errors increase, but the growth or formation of the defects causing the errors again has barely been researched. Frameworks for studying physical defects and relating them to digital errors may have been developed in corporate labs, but there are few, if any, published or accessible methods and models in this area. Therefore, this research aimed to develop, validate, and publish a framework for these purposes.

A framework for studying the connections between physical characteristics and digital errors would provide the basis of further research to possibly diminish digital errors by addressing the root causes of disc failure mechanisms. By applying the framework to naturally and artificially aged discs, comparisons may be studied to help establish a well-defined link between these different types of aging. This would potentially confirm the lifetime estimates and failure mechanism studies already conducted.

## 1.2 Objectives

The purpose of this research was to develop a framework for characterizing physical defects and relating them to digital errors. This framework was then utilized in a validation study which demonstrated its effectiveness and use. The study utilized artificial aging with a few DVD-Rs from several manufacturers.

In the course of developing the framework, three questions had to be answered:

- How should physical defects be evaluated and characterized?
- What is the relationship between observed physical defects and digital errors?
- How do physical defects develop over time in artificially aged media?

Once these were understood, the framework was constructed to be able to characterize the defects and compare them to digital errors. This research utilized several devices and programs. Most notably, a software program was developed as part of the research to bridge the gap between the physical and digital realms.

## 1.3 Delimitations

This study was not designed to exhaustively catalogue and understand, at every level, the defects present on optical discs. The principle objective in the development of the framework and the validation study was to characterize the types and effects of defects found on the discs rather than document all possible defects. The validation study was not a full statistical study and did not compare the brands, disc types, or aging processes used.

In order to understand the basis of the framework developed, the applicable literature on optical discs, both current and past, must be reviewed.

# 2 REVIEW OF LITERATURE

To answer the questions concerning physical defects – how they should be evaluated and characterized, what their relationship to digital errors is, and how they develop in artificially aged media – the relevant literature was thoroughly studied. Sources both current and from the early days of the development of optical discs were found to be very relevant. They not only helped to answer questions, but also showed the desire for and basis of a framework to study physical defects and relate them to digital errors. In this chapter, the composition and data structure of DVDs, including error correction, optical nature, measurements, and failure mechanisms, is reviewed.

## 2.1 DVD Composition

The standard for the Digital Versatile Disc, or DVD, was originally developed jointly by companies participating in a DVD consortium in 1995. In December 1997, Ecma International, formerly the European Computer Manufacturer's Association, published the first standard of the read-only DVD (Ecma International 2001). Ecma was established in 1961 to standardize information communication technology (Ecma International n.d.). The DVD specification set clear standards for physical structure, data format, and read methodology. Pioneer developed the DVD-R, or DVD recordable, shortly after (Worthington 2006). This disc allowed for a write once read many (WORM) variation of the original read-only DVD. The Ecma specification for

DVD-R was released in December 1998 (Ecma International 1998). This section of this thesis presents the basics of the physical structure of the DVD-R specification and its relationship to older disc formats such as CD and CD-R, and a recently developed disc that is similar to a DVD-R.

### 2.1.1 Physical Structure

According to the Ecma specifications, (Ecma International 1998, 2001, 2008) a DVD measures 120 mm in diameter, with a 15 mm center hole used for clamping. The disc consists of several layers of materials stacked on top of each other as shown in Figure 2-1. Two polycarbonate substrates are used which are each 0.6 mm thick and the full diameter of the disc. The polycarbonate on the read side of the disc, called layer 0, is at the bottom of the stack. A metal reflective layer such as aluminum, gold, or silver is placed in a very thin film on top of this and the other substrate, layer 1, is bonded to this layer with an adhesive (Birkett 2002).

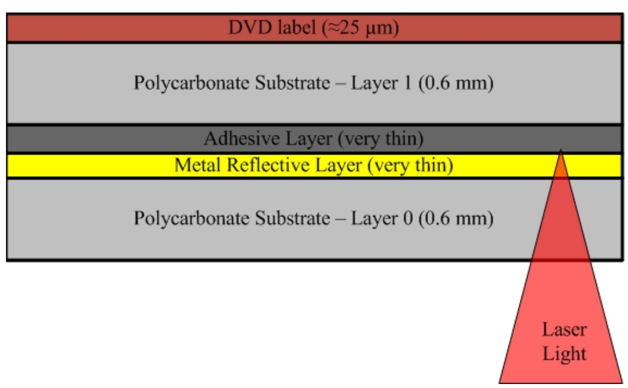


**Figure 2-1: DVD Stack**

The materials used for this bond vary from brand to brand, but are typically ultraviolet curing adhesives (Birkett 2002) (Taylor, Johnson and Crawford 2006). For DVD-R, an organic dye, usually azo, cyanine, or phthalocyanine, is inserted underneath the reflective layer as shown in Figure 2-2 and provides the ability to record data to a disc (Worthington, 2006) (Birkett, 2002) (Lunt, Hyatt, & Linford, Long-Term Digital Data Storage, 2008) (Slattery, Lu, Zheng, Byers, & Tang, 2004). A label is also typically placed on the top of the disc, fully covering the substrate except for the center clamping area.

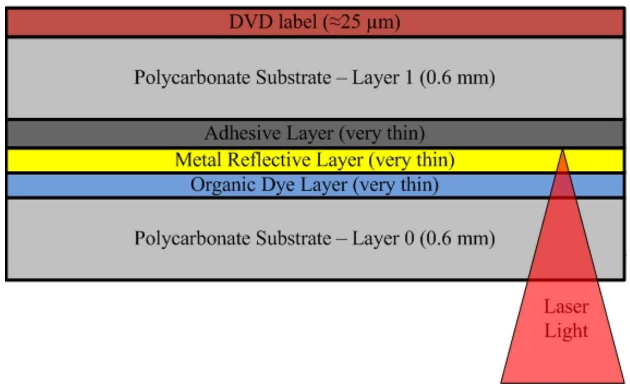


**Figure 2-2: DVD-R Stack**

### 2.1.2 Data Features

In the non-recordable DVD, data is contained on the reflective layer in the form of lands and pits in a single, spiral track. When reading, a laser shines on the metal and the pits are detected by a phase shift in the reflected light as well as an amplitude difference due to the scattering of the light. DVD-R differs in that the dye is changed by the laser during the write phase to allow the light to pass through to the reflective layer. In this case, the marks are detected when reading by an amplitude difference in the reflected laser from the spots in the dye that are marked and those that are not, as shown in Figure 2-3. The image shown is a CD-R's recorded and unrecorded portions side by side as taken with a confocal microscope. Due to similar composition as will shortly be shown, the same view of a DVD-R matches that of the CD-R.

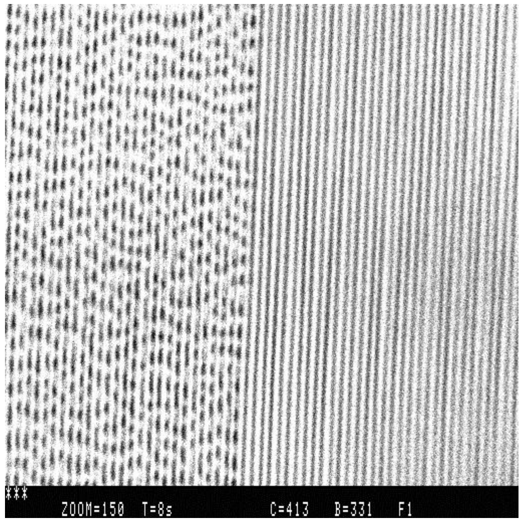


**Figure 2-3: Recorded and Unrecorded Dye on a CD-R (B. Lunt 2005)**

The discs are also created with a groove encoded with tracking information for writing and pit-like gratings for reading. In both DVD and DVD-R, the marks are extremely small, with some as tiny as 0.4 um (Worthington 2006). The total amount of data that can be stored on a DVD is 4.7 GB.

### 2.1.3 Comparison to Compact Discs

The design of the DVD largely resembles that of a CD, except that the features of interest are smaller as shown in Figure 2-4.

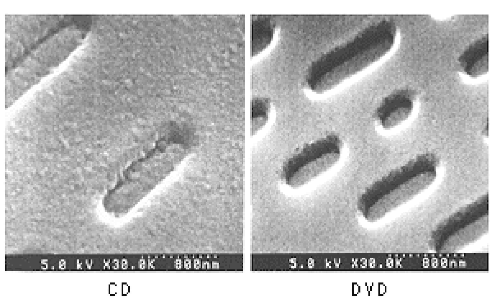


**Figure 2-4: Comparison of CD and DVD Feature Sizes for Read-Only Discs (Worthington 2006)**

Another significant difference between the two formats is their substrate configuration. DVDs, as discussed previously, are formed from two 0.6 mm substrates, but CDs are formed by placing a metallic reflective layer on the top of a single 1.2 mm substrate. Both are manufactured by injection molding processes, have a polycarbonate substrate bonded to a metal reflective layer, and use organic dyes or polymers as the recordable layer in applicable recordable formats (Pohlmann 1992) (Taylor, Johnson and Crawford 2006) (Lunt, Hyatt and Linford, Long-Term Digital Data Storage 2008). Additionally, the optical methods of reading a CD and a DVD make similar use of a semiconductor laser diode focusing on the features. CDs come in both read-only stamped and recordable formats. The stamped disc uses pits just as the DVD does, but the size is at its smallest 0.8 um, about twice the size of the smallest DVD mark, as shown in Figure 2-4. Additionally, as also shown in Figure 2-4, the track pitch for DVDs is smaller, which allows more tracks and therefore more features to fit onto the disc. As a side effect of their smaller feature sizes, DVDs have typically possessed higher rates of errors and have had a shorter life expectancy (LE) when compared to their CD counterparts (Worthington 2006).

### 2.1.4 M-DISC

A new method of DVD fabrication has recently been developed based on research completed at Brigham Young University and furthered by Millenniata, Inc. This disc attempts to overcome the longevity shortcomings of the DVD-R format, yet remain compatible with current reading technology. Instead of using organic dyes as the recording layer, marks are etched into a hard substance like etchings in a rock. The rest of the disc remains largely similar to the DVD-R, with two substrates being bonded together with a metal reflective layer between (Lunt, Hyatt and Linford, Long-Term Digital Data Storage 2008) (Svrcek 2009).

## 2.2 Data Structure and Error Correction

Reading a DVD is a complicated process involving machinery, optics, analog to digital signal conversion, and digital signal processing. Defects in the disc and noise can cause bursts and chains of errors in the read data. Therefore, the storage format of the disc uses error correction codes (ECC) to fix random errors and interleaving to lessen the effects of damage to the data. In order to fully understand the challenges of optically reading a disc, the DVD data structure and ECC use will be explained (Ecma International 1998).

### 2.2.1 Data Encoding

This section will show the transformation of the bits including error checking from data, audio, or video into the form used just before writing to the disc.

#### 2.2.1.1 Scrambling

The data desired to be stored on the disc, called main data, is first sectioned into frames, which consist of identification information, main data arranged into rows, and error checking bytes. A single frame is composed of 2064 bytes total, 2048 of which are main data bytes as shown in Figure 2-5.

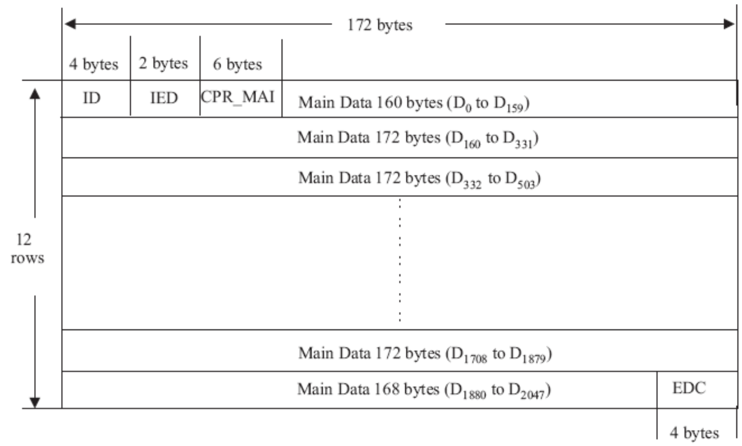


**Figure 2-5: Data Frame (Ecma International 1998)**

The frames are then scrambled by a well-defined procedure involving bit shifts, predetermined values, and exclusive OR bit combinations. This ensures that no bits that lie next to each other in the original data stream remain physically adjacent when placed on the disc. This helps to alleviate problems with multi-bit errors in the reading process, but it still does not solve the problems of recognizing and correcting bit errors.

#### 2.2.1.2 Error Correction Codes (ECC)

When a bit is incorrectly interpreted during the read process, there is no way inherent in the bit itself to know if it was originally a one or a zero. Data redundancy is therefore necessary to enable the recognition and correction of bit interpretation errors. DVDs employ a complex form of data redundancy that allows the original bits to be fully recovered as long as the number of bit errors is not too great in a close proximity.

To do this, 16 scrambled data frames are arranged into 192 rows of 172 bytes each to form an ECC block. Parity check bytes are then added to the end of each row and column. These bytes are calculated by a special mathematical formula from the bytes of the row or column that they represent. 16 parity outer (PO) bytes are added to the columns, and 10 parity inner (PI) bytes are then added to each of the total 208 rows. If a bit changes within the data of a row or column, a recalculation of the parity bytes would show the difference and how to correct the bit. It should be noted that parity checks exist for the parity bytes themselves in the lower right corner of the ECC block. This allows for an error to be corrected in the check bytes themselves. A full ECC block is shown in Figure 2-6.

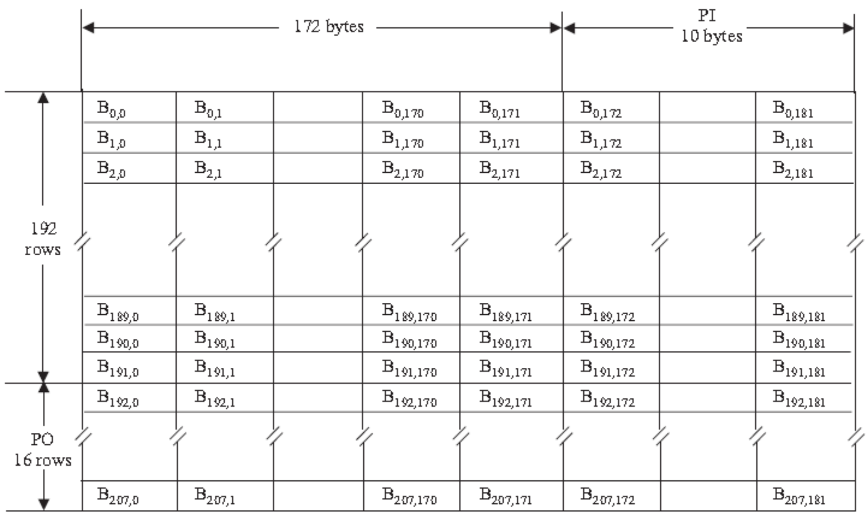


**Figure 2-6: ECC Block Configuration (Ecma International 1998)**

### 2.2.1.3 Interleaving

Due to the reasoning that larger errors tend to occur in groups on a disc, interleaving is used to spread and as a result lessen the damage that can be inflicted on the data by chains of errors. The ECC blocks are interleaved to form entities designated as recording frames. A recording frame is composed of 12 rows of the ECC block data followed by one of the 16 PO rows from the end of the block. From a single ECC Block, 16 recording frames of 2366 bytes each are constructed.

#### 2.2.1.4 Modulation

If data were stored on the disc exactly as it was comprised in the recording frames, there would be two major difficulties when attempting to read the data back optically. First, an optical pickup detects transitions, such as when the signal detects a difference in amplitude between marked and unmarked dye. These transitions must be spread out or the read channel may think that one feature was just a continuation of the last one. In other words, it is difficult for an optical disc system to read a series of marks such as those representing 01010101. The read channel would likely be filled with errors due to the difficulty of detecting multiple adjacent features. Second, a lack of transitions such as a string of 100 ones or 100 zeros would cause timing issues and would prevent the laser from knowing exactly how many ones or zeros were present in the data. To solve these problems, recording frames are modulated before they are placed on the disc.

Modulation is the process of converting a digital signal, such as a series of ones and zeros, into a continuous time signal, such as an optical disc read signal (Bergmans 1996). In applying modulation to the recording frames, the data is not yet converted into an analog signal, but is instead modified to be able to easily complete this conversion later in the process. As defined in the Ecma DVD specification, the data of the recording frames is modified from 8-bit bytes to 16-bit code words with the following limitations. Each code word must have at least two and at most ten zeros in between two ones. These length limitations prevent both issues mentioned above; no two transitions would be too close together and the laser would not have timing errors due to a lack of transitions.

#### 2.2.1.5 Synchronization and Writing

As the final step before writing, synchronization data is added to the modulated data to form a physical sector. Each row of the modulated recording frame is split in half and special SYNC bytes are added to each to form a single row of the physical sector. The bits are then represented on the disc through either prerecorded pits or a series of darker dye marks for the DVD and DVD-R formats respectively.

### 2.2.2 ECC Errors

Without the ECC mechanism, common errors would render the data read back from the disc largely useless. A single bit error in an audio file, video file, or application stored on a DVD may prevent the file from being read at all by a computer. As explained above, the ECC block arrangement adds PI and PO bytes to the edges of the data block to help recognize and fix bit errors. This allows the majority of errors to be fixed, but cannot always fix every error, especially in the case of longer chains of errors (Coene, et al. 2001). Additionally, reading a disc optically by nature is probabilistic. This means that some errors can be "fixed" simply by re-reading the disc. However, larger chains of errors will occur in the same location and subsequent reads will display the same results. The DVD specification for ECC allows for several error types to be reported in order to understand the extent of these errors, which can be due to problems in the read signal or defects present on the disc itself. These error types and their respective values form the best method of measuring the current state or health of a DVD. Many of them are also highly correlated to one another due to the information they report. This section defines each error type and their correlation to one another.

#### 2.2.2.1 Error Types

Many error types have specific limitations, or maximum values, that can be reported for the disc data to be considered recoverable. Outside of these limits, unrecoverable errors may be encountered and data may be lost. Each error type with an associated limit is defined as follows.

##### 2.2.2.1.1 PIE

A parity inner error (PIE) is when a single row of an ECC block has at least one byte in error (Ecma International 1998). There is no hard limit to the amount of these errors in a single ECC row.

##### 2.2.2.1.2 PIE Sum 8

The PIE Sum 8 value is a running total of the sum of PIE errors in the last eight consecutive ECC blocks. This is used to limit the number of PIE errors that occur in certain area at a maximum value of 280 (Ecma International 1998) (DaTARIUS Group 2005).

##### 2.2.2.1.3 PIE 8

PIE 8 errors occur when the PIE Sum 8 values are over the threshold. Thus, the number of PIE 8 errors corresponds to the number of times PIE Sum 8 is over 280 on a disc. There are no specified limits to the number of PIE 8 errors present as it is not common in the literature but is reported by analysis software.

##### 2.2.2.1.4 PIF

A parity inner failure (PIF) occurs when more than five PIE errors are present in a single ECC block row. In other words, more than five bytes in a single row have errors. This error type signifies that the parity bytes are not able to be used to recover the data in the row, and therefore the entire row is marked as bad. It is also known as "PI-uncorrectable." The number of PIF errors in a single ECC block cannot be more than four according to specifications (Ecma International 2008).

#### 2.2.2.1.5 PIF Bytes

PIF Bytes, although used in the literature (Lunt, Bourgeous, et al. 2010) and reported by analysis tools, are not well documented. Clearly related to PIF errors, the exact connection is unclear.

#### 2.2.2.1.6 POF

A parity outer failure (POF) occurs when more than eight bytes have at least one error in a single column of an ECC block. This represents an unrecoverable error. The specifications call for no POF errors to occur as a single error means data has been lost (DaTARIUS Group 2005).

### 2.2.2.2 Correlation

Due to the similarity of the information present between some error types, such as the fact that too many PIF errors will most likely lead to a POF error, some redundancy exists between them. A study was recently conducted which correlated the average and maximum values for each error type. The result was that the most unique information was presented by PIE 8 max, currently the recommended method of measuring the status of a disc (Ecma International 2008), POF average, and PIF Bytes max (Lunt, Bourgeous, et al. 2010).

## 2.3 Reading a Disc Optically

In order to read the data as stored on an optical disc, a semiconductor laser diode is used to reflect light off of the metal reflective layer. A change in phase or amplitude is used to detect a transition in the disc depending on the format. This transition is the difference between the lands and pits or the normal and written dye. After this, the read signal is quantized into a string of ones and zeros by comparing whether the voltage is over or under a threshold value. Because of the nature of the reading process and quantization, it is susceptible to noise.

Sources of noise in optical reading are due to electronics, the laser itself, disc motion, and especially the disc media (Finkelstein and Williams 1988). Media noise could signify roughness or deformations of the surface of the polycarbonate or the reflective layer, e.g. a badly formed pit (Pohlmann 1992). This noise is "primarily due to transition jitter" as stated by Bergmans, which is a difference in the timing of the optical pickup compared to the timing of the features. It is also documented that "transition jitter is typically the dominant type of noise" in optical disc reading (Bergmans 1996). This effect, along with the other noise present, causes the read process to incorrectly interpret the ones and zeros on the disc. In other words, noise leads to random errors in the decoded bit stream (Coene, et al. 2001).

However, there are typically defects present in or on the disc which also interfere with the read signal and cause dropouts. This is when the signal amplitude drops significantly for an extended period of time. Common causes include "dust, fingerprints and scratches on the disc surface, and dynamic variations of the bit rate that are caused by disc eccentricity". Defects such as pinholes or scratches in the reflective layer can even "cause the replay signal to vanish during tens or even hundreds of bit signals" (Bergmans 1996). These cause long strings of errors in the reading process; therefore, they are termed burst errors and are usually much longer bitwise than the random errors encountered from common noise sources. The destructive effect of burst errors on the data shows why the data is protected by encoding and interleaving techniques (Pohlmann 1992). There are still other ways that the disc and the data stored within can be damaged, however. Almost always, these are related to disc degradation. Degradation methods must therefore be considered.

## 2.4 Disc Degradation

From the moment a DVD is formed on the manufacturing line, it is susceptible to error-causing defects and degradation. Many have studied the effects of this degradation in order to estimate the life expectancy for different formats of optical discs. In order to simulate the process of a disc aging naturally over a period of many years, standards have been developed into a process called accelerated or artificial aging. From studies performed on naturally and artificially aged discs, several mechanisms of degradation have been revealed. A further exploration of the studies performed and their results is necessary to understand the current state of knowledge in the area of disc degradation. These will be explored along with an explanation of accelerated aging techniques, known failure mechanisms, manufacturing defects, and the effect of degradation on digital errors.

### 2.4.1 Studies

The majority of studies in the field of disc degradation involve lifetime estimation (LE) of a certain brand or format of disc. Other studies have focused less on an actual estimate and have instead been directed to observe and categorize the degradation methods of discs. This research will focus mainly on the latter. While many of both types of studies have involved CDs and CD-Rs, fewer have included DVDs and DVD-Rs. However, due to their similarities in composition and manufacturing, both are beneficial for analysis. Only general observations and findings will be reported here. Results specific to degradation methods will be explored further later on.

The National Institute of Standards and Technology (NIST) performed a study in 2004 that, although too small to make statistical estimates, indicated that the dye type used in recordable optical disc formats affects the lifetime of the disc. In general, they found that CD-R media that used phthalocyanine dyes performed better than other types. Azo and cyanine dyes displayed vulnerabilities to humidity, temperature, or light. Information on DVD-R dye types was not readily available during the study, and therefore no concrete determinations could be made based on dye type of DVDs. Nevertheless, the results did show degradation differences between even similar dyes used in DVD-Rs, most likely due to manufacturers making modifications to stabilize the dyes (Slattery, et al. 2004).

The Library of Congress (LoC) published results the same year of a study using CDs from their own collection. Two different sections of the study tested naturally- and artificially-aged discs. Again, the study was too small to make formal statistically-based conclusions on LE, but their findings were very significant and showed that discs degrade over time. In a relatively short time of nine years, the naturally- aged discs had already begun to show signs of degradation with a slight increase in unrecoverable errors. Measurements of the condition of the disc such as jitter also increased. As a final note to the natural test portion of the study, it was noted that "Physical examination using a microscope is also important to look for surface defects or other physical abnormalities." The accelerated aging section revealed a few of the major degradation methods of optical discs (Shahani, Manns and Youket 2004).

In 2005, another study was published by Iraci analyzing the stability of various optical disc formats. The discs were separated by dye type and even reflective layer material. Different degradation mechanisms were observed in the course of the study. Most importantly, however, the study proved that CD-Rs with phthalocyanine dye were the most stable format. DVD-R discs showed better results than CD-Rs without phthalocyanine, and DVD-RW was shown to be the most unstable of all (Iraci 2005).

A study was conducted in 2009 which included the M-DISC from Millenniata, Inc. The testing conducted compared each of six brands of archival and high quality DVDs after aging them in an accelerated manner. In the end, the M-DISC was the only one that still passed DVD specifications with a PIE Sum 8 error value lower than 280. Two of the disc brands failed to analyze at all after aging. The data was confirmed to be recoverable from the M-DISC (Svrcek 2009).

As for an actual estimate of disc lifetime, many studies have established or utilized standards for estimating the number of years a DVD will last before failing. Suffice it to say that the research often disagrees, with estimates "ranging from about 10 years to as many as 300" (Lunt & Linford, Family History Archives: Research on New Media). It should also be noted that these values represent an average LE, and do not signify when the first disc of a set actually fails (ibid).

### 2.4.2 Accelerated Aging

Almost all studies which touch on disc degradation involve a form of accelerated or artificial aging. This is the process of simulating the wear and environmental conditions that optical discs are subjected to naturally over years within a shorter time period. Typically the discs are subjected to elevated temperature, humidity, and sometimes light in periods ranging from hours to days. A standard for this process without light was released in June 2007 by Ecma (Ecma International 2008). In the studies discussed above, not all used light in accelerated aging. However, in the NIST study, the conclusion was reached that "the effects of direct light exposure cannot be ignored" in accelerated testing (Slattery, et al. 2004). Accelerated aging has helped to reveal the failure mechanisms that are believed to occur naturally over time within the timespan of a single study.

### 2.4.3 Failure Mechanisms

The literature has shown repeatedly that disc failures can be attributed to four main mechanisms. These are dye degradation, corrosion, oxidation, and delamination.

#### 2.4.3.1 Dye Degradation

Dye degradation is one of the most common failure mechanisms in recordable discs. Due to the fact that most recordable discs contain organic dyes, these layers are vulnerable to degradation by elevated humidity or temperature. Additionally, these are typically light-sensitive and are susceptible to elevated levels of light treatment (Lunt and Linford, Towards a True Archival-Quality Optical Disc 2009).

Optically speaking, dye degradation has a severe effect on the ability of the laser to read a disc due to the loss in contrast. This is not a failure mechanism that can be viewed with the naked eye or even by microscope. Because it is only detected by the optics of the disc drive, this failure is extremely difficult to measure. Often this is the failure mechanism attributed to failures where no other failure mechanisms can be observed.

#### 2.4.3.2 Corrosion

The result of corrosion on an optical disc is a "localized loss of the reflective layer material" (Lunt and Linford, Towards a True Archival-Quality Optical Disc 2009). It is usually manifested by pinholes in the reflective layer or other similarly damaged areas of the disc. These failures can be caused by improper sealing at the edges of the disc or by a bad manufacturing process. This improper sealing is often due to the adhesive (Birkett 2002). A bad manufacturing process is typical of one that is still being developed or perfected; therefore, this cause was more common during the early days of optical disc manufacturing. Studies have mentioned that the early CD manufacturing process produced discs which failed faster than later products (Shahani, Manns and Youket 2004). This same idea can be extended to include the DVD manufacturing process.

The effects of corrosion on the data of the disc are evident in Figures 2-7, 2-8, and 2-9 from the Library of Congress study, which show increasingly magnified views of the corrosive damage. It is clear from the images that corrosion is visible even to the naked eye. A single, tiny pinhole such as this can cover literally hundreds or even thousands of tracks and a large amount of associated data on a DVD.

**Figure 2-7: Corrosion of Reflective Layer (Shahani, Manns and Youket 2004)**

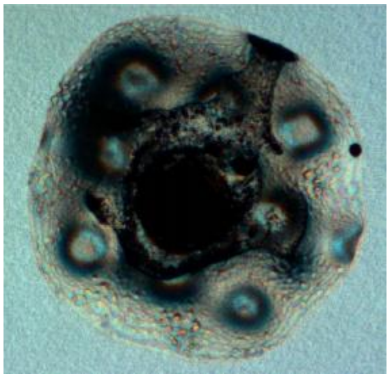

**Figure 2-8: Close-Up View of Corrosion (Shahani, Manns and Youket 2004)**

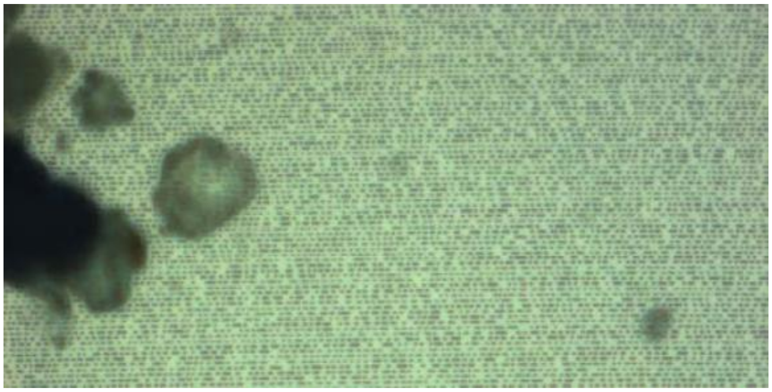

**Figure 2-9: Close-Up View of Effects of Corrosion Damage on Data (Shahani, Manns and Youket 2004)**

The study by Iraci showed similar results in the form of pinholes in DVDs as seen in Figures 2-10 and 2-11. These views are shown from the base side of the disc.

**Figure 2-10: Example of Pinholes in Reflective Layer (Iraci 2005)**

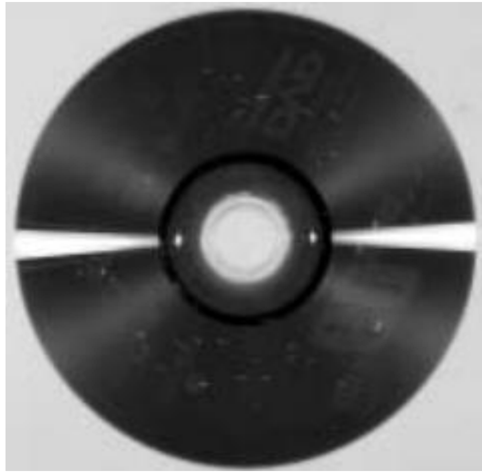

**Figure 2-11: Example of Pinholes in Reflective Layer (Iraci 2005)**

Since corrosion typically occurs in the vital metal reflective layer, the data is often greatly affected.  In fact, it has been said that when the metal layer is compromised, “the data on the disc is also usually compromised” (Lunt and Linford, Towards a True Archival-Quality Optical Disc 2009).  Gold is often used as the reflective layer in DVDs due to “its inherent resistance to oxidation and corrosion” (Lunt and Linford, Family History Archives: Research on New Media n.d.).

#### 2.4.3.3 Oxidation

Oxidation is actually a form of corrosion, but is so common that it is placed in its own category.  Due to the same causes as corrosion, this is most likely when the edges of disc are not properly sealed and the metal layer oxidizes (Shahani, Manns and Youket 2004).  The effects of oxidation can be seen in Figures 2-12 and 2-13.

**Figure 2-12: Oxidation of CDs after 500 Hours of Accelerated Aging (Shahani, Manns and Youket 2004)**

**Figure 2-13: Audio CD Shown From Base Side after 84 Days of Aging (Iraci 2005)**

Observed mainly after elevated temperature and humidity, the reflective layer of the discs appears to become transparent to the naked eye. The effects on the data are the same as corrosion, but more widespread as it typically covers the entire disc.

### 2.4.3.4 Delamination

Delamination is when the layers of polycarbonate begin to separate due to a failure of the adhesive. Delamination may also include the label peeling from the top of the disc, but this does not usually affect the reflective layer in DVDs, since the reflective layer in DVDs is protected by

0.6mm of polycarbonate on each side. Delamination can be made to occur after a 92° C water bath, which is just below the boiling point of water. Other more common factors that lead to adhesive failure are temperature, humidity, and light (Lunt and Linford, Towards a True Archival-Quality Optical Disc 2009). When the disc has begun separation, it can have the appearance of bubbles within. A feel test may be conducted by observing if the layers move between fingers when rubbed together. Once again, the failure of the adhesive may be due to improper sealing of the disc edge. Examples of this occurring are shown in Figures 2-14, 2-15, and 2-16. It should be noted in these figures that CDs are shown, not DVDs. Because CDs only have one substrate, the reflective layer is shown peeling off with the label.

**Figure 2-14: Metal Layer Separating From Substrate (Shahani, Manns and Youket 2004)**

**Figure 2-15: Audio CD Delaminating after 84 Days of Aging (Iraci 2005)**

**Figure 2-16: CD-R Delamination after 21 Days of Aging (Iraci 2005)**

Delamination is often catastrophic to the data on the disc as either the reflective layer peels off or the disc can no longer be read in a drive. Although dye degradation has been seen as the most common degradation method to end the life of a disc, “other research has shown that delamination is a more likely failure mechanism” (Lunt and Linford, Towards a True Archival-Quality Optical Disc 2009).

### 2.4.4 Manufacturing Defects

In order to understand all possible sources of errors in the disc, manufacturing defects also need to be explored. These range in shape, size, and nature and can possibly accelerate the failure mechanisms mentioned. Due to the complicated processes of disc creation and manufacture, there are many opportunities for things to go wrong. In fact, it has been said of optical discs that "problems [such as defects in the discs] can occur anywhere in the manufacturing chain" (Pohlmann 1992). Malformed pits in stamped media, sometimes "caused by temperature inconsistencies in the mold," means errors will be encountered (ibid). Dust particles, usually quite harmless on a disc's reading surface, "would disrupt large amounts of data" when included in the polycarbonate or at the reflective layer (ibid). Any foreign particle at the reflective layer during manufacturing causes problems, as it may "prevent the metal molecules from adhering to the disc substrate properly, creating a pinhole in the metal layer" (ibid). Pinholes such as this can occur very often and, just as seen with corrosive pinholes above, cause often irreparable damage to data (ibid).

The DVD specification actually specifies which types and sizes of defects are allowable on a disc. Air bubbles, or air trapped in the polycarbonate layer, should be less than 100 um. Black spots which cause birefringence, or double refraction of the light, should not exceed 200 um, and black spots not causing birefringence should not exceed 300 um. Limits on defects within a certain vicinity are also specified. An area of 80 mm in the direction of the tracks needs to have the total length of defects larger than 30 um not be longer than 300 um, and at most only six of these defects may be present (Ecma International 1998).

One type of manufacturing defects is inclusions, which are particles of foreign matter that get within the disc polycarbonate or on top of the reflective layer. Failures due to inclusions have not been studied in depth in publicly available literature. They are created during the typical manufacturing process. Although it is thought that new inclusions can be created and observed on a disc after manufacture, it has yet to be documented or observed.

Devices have been created to measure the amount and sizes of manufacturing defects. While these are only available typically in automated manufacturing lines, one such device can check for metal spots and scratches, injection flaws, inclusions, surface scratches, surface spots, lint, stains, and gaps in the bonding layer (Dr. Schenk GmbH 2011).

### 2.4.5 Relationship to Digital Errors

Relatively little is known of the exact nature of defects on discs except what is discussed above. In addition, surface contaminants such as fingerprints and stains are quite common on optical discs, as can be observed on a typical DVD that has been used for any length of time. However, it has been documented that fingerprints, dust, and scratches do not have much effect on the read process due to the way the beam focuses beyond the objects (Optical Storage Technology Association 2004). This only applies to smaller contaminations where the amplitude loss of the signal does not affect the jitter or the signal to noise ratio (SNR). However, large excessive fingerprints, dust, or scratches can cause enough amplitude loss that the SNR is lowered and the jitter increases. This directly translates into readback errors. Another source mentions that this problem was fixed in CD reading by filtering out low-frequency components of the signal (Immink 1995).

Perhaps the largest "blind spot" in the area of disc degradation is a lack of understanding how the failure mechanisms and defects precisely affect digital errors. For example, is it possible to be able to identify which digital errors can be attributed to each failure mechanism? It is believed that the bulk of this research has been completed in corporate labs. However, these results have not been published nor made publically available. Future work in this area should seek to understand the connection between physical defects and digital errors. Furthermore, the exact physical nature of what occurs as these defects are formed should be studied.

### 2.5 Summary

Optical discs have been proven to fail in relatively short periods of time. This is especially true for recordable formats such as DVD-R. Because of this, studies have identified the major sources of disc degradation and estimates of the lifetime of discs. Which combinations of failure mechanisms lead to unrecoverable data and what exactly happens at the physical level of the disc is still relatively unexplored. This section provided an overview of the basics of the DVD-R technology and modes of failure, including physical structure, data structure, error encoding, reading, and degradation. This was done to lay the basis of understanding what effects physical defects have on stored data. While studies have accepted that this is true and that errors are caused by defects, they have not explored the exact mapping between them. Therefore, there is currently a need to be able to map digital errors to physical defects in order to more fully understand the interaction between them. This information would benefit not only the industry and interested community, but the end consumer of optical discs. From the literature sources mentioned, a framework to perform this function was developed as will be explained next.

# 3 METHODOLOGY

Due to the lack of a publicly available and mature framework for studying the physical defects of DVDs and correlating them to digital errors, research was undertaken to fill this gap. The development of a framework was comprised of trial and error, research, and brute force approaches. In other words, an empirical rather than theoretical approach was taken. In the course of the framework's development, several tools were identified to help in identifying the physical characteristics of the disc. Since no tools were available to map these gathered information sources to digital errors, a software tool was created. In the end, this tool was eventually expanded to perform analysis and present the information provided to it in a useful manner. Initial tests were run to certify that the created software was able to perform the analysis needed. After identifying the tools and the outline of the framework, this research consisted of a study to validate it. In short, the study consisted of fourteen DVD-Rs being run through iterations of data collection and accelerated aging. Analysis was then performed on the data gathered to prove the effectiveness of the framework. This section will explain the tools utilized, the initial tests run, and the data collection and analysis of the validation study.

## 3.1 Tools Utilized

Several devices or programs became essential to data collection or analysis in the framework. For data collection, these tools were chosen for their ability to help determine the failure mechanisms or physical conditions of the disc. An additional tool was created to aid in the analysis and presentation of the gathered information. Here follows a description of each tool along with its specific application or utility in the framework.

### 3.1.1 Environmental Chamber

As shown previously, the industry standard for studying the effects of age on discs includes treating them with elevated levels of temperature, humidity, and light. Therefore, a BHD-203 environmental chamber manufactured by Associated Environmental Systems was employed to perform these treatments in a sealed and controlled location. At its core, the chamber provided the ability to control humidity and temperature using a heat generator and a large container of water. The device allowed for profiles to be set which followed a set of steps. Each could be configured to change the controlled factors or hold them at a set value for defined periods of time. A standard was created which was reused throughout the testing to artificially age the discs.

In order to add the essential condition of elevated light, metal halide lamps, Eurflood UHI-150DM/UVPs, were inserted at the top center of the chamber with an external switch. The lamps emit light similar to sunlight, even including part of the UV spectrum. Their spectral output is shown in Figure 3-1.

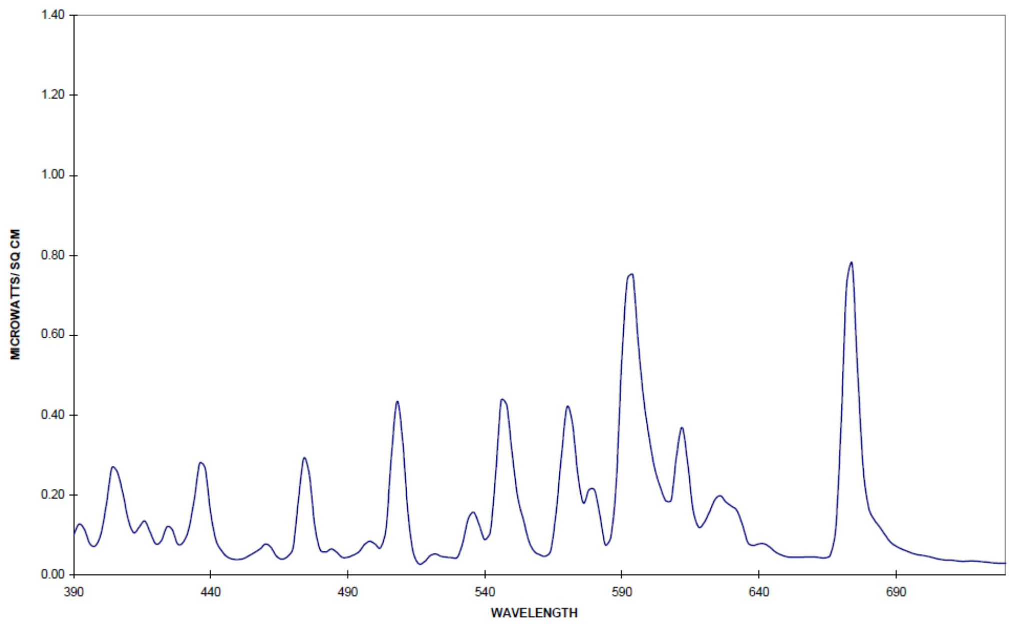


**Figure 3-1: Metal Halide Lamps' Spectral Output**

The lights were switched on when testing was started and switched off when the testing profile was complete. It was absolutely essential that the lights were turned off when the chamber stopped controlling humidity and temperature. If not, the discs would have been melted due to the extreme heat produced by the lights in the sealed chamber.

A rack designed to hold 18 discs was used to hold the discs in the chamber at standard positions. It placed the discs on pegs with optional washers to vary height and facing data side up towards the lights in the center. A pyranometer, the Omega HH306A, was utilized while varying the height of the disc placements to ensure that each disc received the same amount of light. Pictures of the environmental chamber from the outside and with the rack are shown in Figures 3-2 and 3-3.


**Figure 3-2: External View of Chamber**

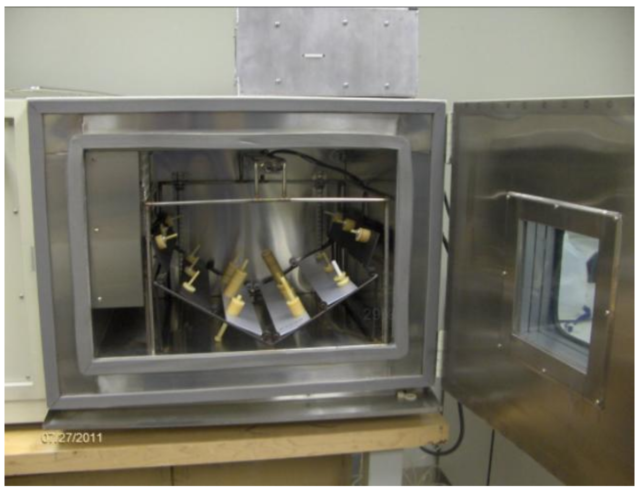

**Figure 3-3: Chamber with Rack**

The environmental chamber also had software available with a serial connection. This software was installed on a specialized computer designed to analyze optical discs, called a Shuttleplex.

### 3.1.2 Shuttleplex Media Analyzer

In order to determine the digital errors on the disc, a Shuttleplex Media Analyzer was used. This device came with software called DriveAid in combination with a high quality DVD drive to identify digital errors. When the analysis was run, DriveAid reported the number of errors in each ECC block on a disc. This information was then exported to a CSV file. The error types utilized from this device and accompanying software were PIE, PIE Sum 8, PIE 8, PIF, PIF Bytes, and POF. The CSV also contained information about the average, maximum, and total values for each error type on a single disc.

Due to the size of a single ECC block, efforts were made to find the exact location of the errors as opposed to counts for each block. This proved to be outside the scope of this study and resources available due to the fact that the ECC chip in the DVD drive was what reported the counts of errors to the software. In order to get a finer granularity of information, the chip itself would have needed to be replaced.

The DVD drive on this device also served as the writer for almost all DVDs in conjunction with the free InfraRecorder software. The only discs that were not burned with it were the Millenniata M-DISCs, as these required a specialized writer. During the course of this study, a single set of data was used when writing to the discs consisting of almost 4.7 GB of DVD video.

### 3.1.3 M-WRITER

Although the M-DISCs can be read by any typical DVD drive, they can only able to be written by a DVD drive created specifically by Millenniata for this purpose called the M-WRITER. This drive, with the InfraRecorder software, was used to write the aforementioned video data onto the M-DISCS.

### 3.1.4 Dr. Schwab

The argus XE device, made by dr.schwab Inspection Technology and commonly referred to as the Dr. Schwab, was used to inspect the overall physical condition of the disc. This device is an industry standard tool often utilized for post disc creation inspection. It has the ability to record data concerning the shape and optical properties of a disc. In this study, it was utilized to record the reflectivity of the data side of the disc. Accompanying software called argusEco was then used to read the measurements made by the device and create an image of the disc reflectivity. It was believed that this device would provide information about failure mechanisms that could not be observed with the eye, such as dye degradation, since it analyzed the disc with a laser.

### 3.1.5 Magnification Devices

Two of the most heavily utilized devices were microscopes used to manually search for physical defects on the discs. The first was a variable-zoom binocular microscope which used either an overhead light angled at 45° or a transmissive light from beneath. It had the ability to magnify from 7.5x to 75x in a continuous manner. This will be referred to as the "zoom microscope". The second was known as the "metallurgical microscope" and possessed an inverted stage which provided light through the objective itself. This microscope used ocular lenses of 10x magnification with objectives of either 5x, 10x, 20x, or 50x for a total magnification of 50x, 100x, 200x, and 500x. The metallurgical microscope proved to be the more useful of the two due to its higher magnification capabilities and was consequentially used most often. Each device was utilized in the framework to identify physical marks in or on the discs' reading surfaces. While these proved very useful, the time taken to look at each individual mark on a disc was determined to be unacceptable. This problem was compounded as the disc was degraded and especially as it gathered scratches and other surface blemishes. The solution was to use smaller and more mobile magnification devices. These tools, called eye loupes, provided the ability to inspect a disc at magnified levels of 10x and 16x without placing it on the stage of a microscope. They allowed the ability to be able to easily identify new or interesting marks.

### 3.1.6 Camera Image

In order to record macroscopic information concerning the state of the disc, a digital camera and mount were utilized. The mount consisted of a shroud, two side flood lights of 40W each, and a camera mounting screw. The shroud covered a large area over the disc in order to prevent dust, exterior lights, and various reflections from interfering with the picture. When the digital camera was mounted on the screw, the lens was allowed through the shroud by a hole. Two flood lights were used on either side of the mount to give enough light for the disc to be seen while minimizing the amount of reflections on either side. Partway through the validation study, silk covers were added in front of the flood lights to disperse light and minimize reflections on the disc. The thin layer of silk was folded three times to obtain the optimal picture. The mount with the shroud and lights is shown in Figure 3-4. The same with silk covers is shown in Figure 3-5.

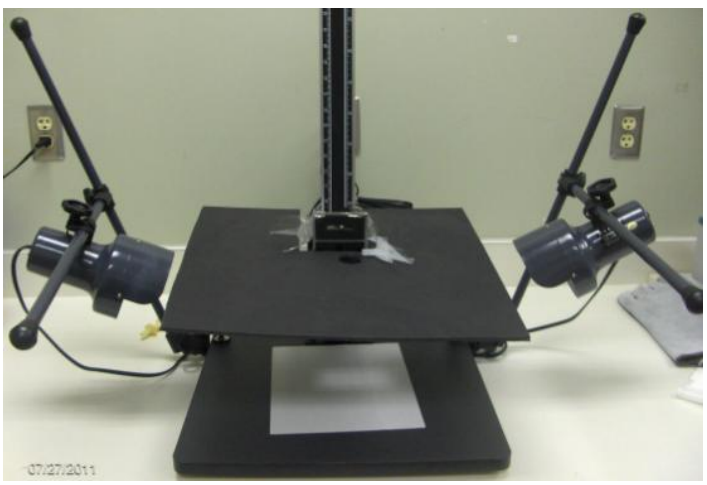


**Figure 3-4: Mount with Shroud and Lights**

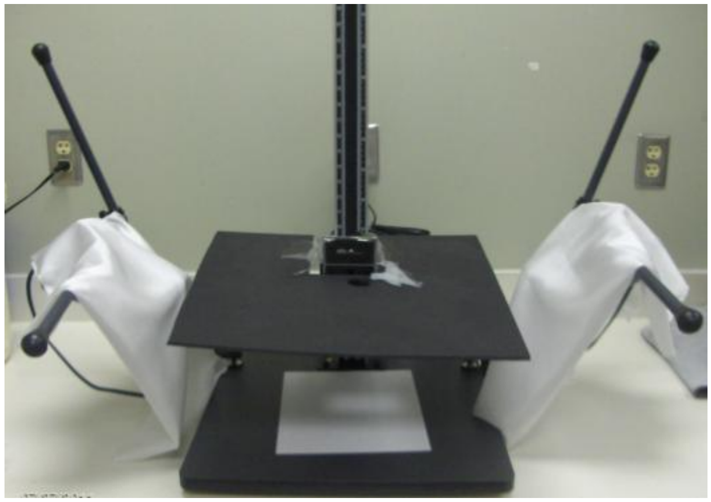

**Figure 3-5: Mount with Shroud, Lights, and Silk Covers**

### 3.1.7 SectorDraw

Perhaps the largest portion of the framework consists of a tool that was created by this and a previous researcher specifically to aggregate the gathered information and present it in a readable format. This program, called SectorDraw, originally began as a way to represent the physical location of the digital errors reported by the Shuttleplex. However, its role was expanded by the added ability to display overlays on the digital error mapping. The program was also extended to show multiple disc representations at one time and to handle sets of data analysis. The interface was then able to be used to draw comparisons and understand the physical nature of the errors. SectorDraw could be termed the ultimate tool of the framework as without it, the gathered data could not be easily compared. In order to understand fully the features of SectorDraw, its digital error mapping functionality, overlays, and ability to display and analyze sets of data must be explored.

#### 3.1.7.1 Shuttleplex Analysis

SectorDraw represented each of the types of digital errors on each track of the disc in a graphical interface. The smallest optical disc unit with valuable data available was ECC blocks, therefore these were chosen to be the building blocks of the disc representation in the software. In order to use this data, each block's radius, start angle, and end angle were calculated precisely. This data is used by SectorDraw along with the digital error analysis from the Shuttleplex to show each error's precise physical location in the disc, as shown in Figure 3-6. In this image, the blue sections represent ECC blocks with no errors, and the other colors represent varying amounts of errors in ECC blocks as explained below Figure 3-7.

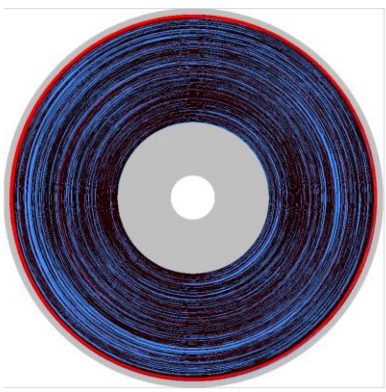

**Figure 3-6: SectorDraw Digital Error Representation**

Due to its basis in the Java programming language drawing API, the number of tracks shown on the screen at one time was limited. Therefore, the program also had the ability to change the focused center of the disc as well as zoom in as needed, even to a point where individual data tracks could be observed as shown in Figure 7.

**Figure 3-7: SectorDraw Displaying Individual Tracks**

Only one primary error type may be represented on the screen at a time, which is selectable from a control on the main screen. Any error type reported by the Shuttleplex can be drawn in the software. To reflect the severity of the errors represented, SectorDraw normalizes the color of this type to range from dark to bright red. This means that at a glance, the intensity of the errors in a certain area can be evaluated. This also shows patterns of errors in common error types which would otherwise not be apparent. For example, the PIE error type, typically encountered throughout the disc, shows darker and lighter areas when viewed for a disc. The brighter red color would represent a relatively higher quantity of errors within an ECC block and would be easily visible for areas with concentrated high numbers of errors. Additionally, SectorDraw has the ability to select a secondary error type to be drawn. This error type, using the same graded color scheme except with green, would show similar information for the second type. When a single ECC block has both error types present, the color is shown as yellow and is again brighter for relatively higher counts of errors. This behavior is shown in Figure 3-8.

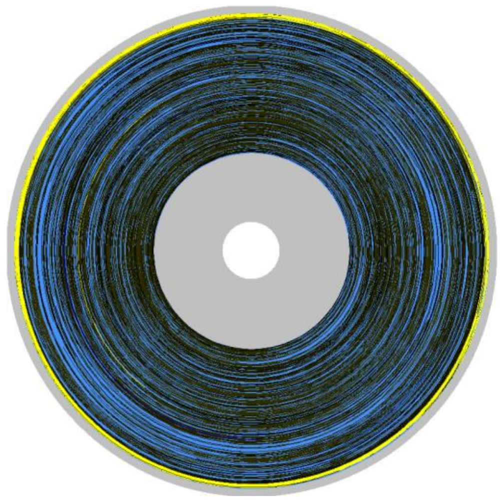

**Figure 3-8: SectorDraw Displaying Two Error Types**

In order to expose as much information as possible in a single interface, ECC blocks can be selected and parameters such as error counts, radius, start angle, and end angle may be viewed. This causes the block to be represented as a dark blue color and the relevant information to appear in a console as shown in Figure 3-9. Only one ECC block may be selected at any time for each disc represented.

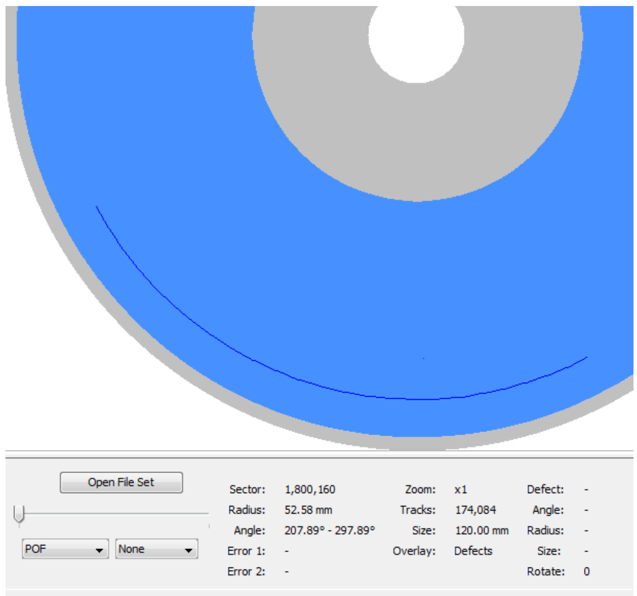


**Figure 3-9: SectorDraw Selecting ECC Block**

#### 3.1.7.2 Overlays

Due to the large quantity of data available from tools other than the Shuttleplex, the concept of overlays was devised. In short, SectorDraw can easily be extended to include images that are either drawn with the Java API or come from an existing picture. The digital error representation does not identify a standard point of reference in the physical world; in other words, the start of the first ECC block is unknown except to an optical drive reading a disc. Therefore, overlays such as a picture taken of a disc may need to be rotated to match observed physical characteristics to the digital error representation. Each overlay can be controlled individually within the software to modify rotation or transparency. Here follows a description of each overlay available and additional feature present in SectorDraw.

##### 3.1.7.2.1 Manually Observed Defects

To represent the manually observed defects on a disc, a file format was created to store information concerning the location in angle and radius, size, and other identifying information of defects for a single disc. Due to the way that the defects are represented using the Java drawing API, a rotation of the defect was also needed to draw it as close to the actual orientation as possible. These files were automatically created from the pictures taken when the defects were observed in the microscopes. SectorDraw uses the information stored to draw an accurate depiction of the defect on top of the tracks and ECC blocks shown. An example of this may be seen in Figure 3-10.

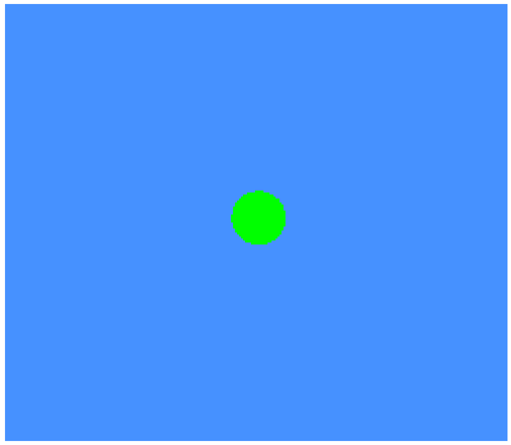

**Figure 3-10: SectorDraw Observed Defects Overlay**

Similar to the blocks of the disc, a single defect may be selected to view additional information. When this is done, the defect changes color to white and certain data is presented in the console as shown in Figure 3-11. The information displayed includes the defect number, degrees of rotation, angle, radius, and size in micrometers.

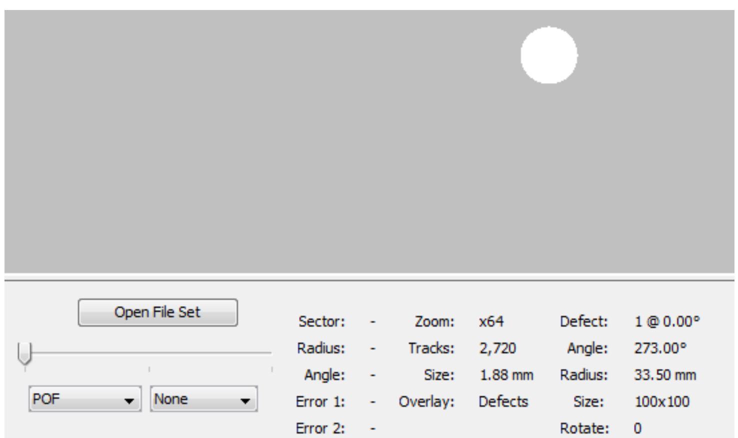


**Figure 3-11: Selected Defect with Information Displayed**

Due to the fact that some defects are very small and are extremely hard to see, especially when overlaid on top of many error blocks, an option exists to enable or disable highlighting of the objects. When highlighted, a white circle is drawn around each defect as shown in Figure 3-

12. Note that this image is zoomed in to show the circle clearly and is not the actual size of the highlighting marks.

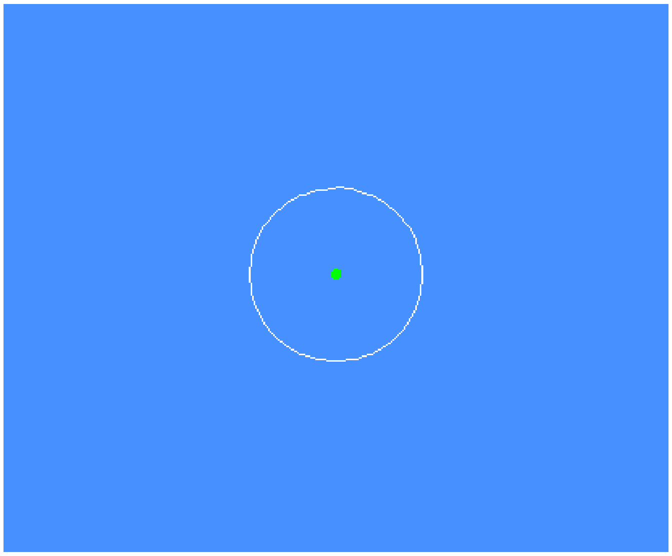

**Figure 3-12: Highlighted Defect**

### 3.1.7.2.2 ECC Block Centers

As discussed, burst errors due to defects or other causes likely cover tens to hundreds of adjacent tracks. However, an ECC block covers an angle of 197° in the inner radial tracks to about 82° in the outer tracks. This makes identifying the angle of a defect within a collection of adjacent digital errors very difficult. To mitigate this issue, an overlay was constructed to find relative concentrations of ECC blocks with errors. In short, this overlay helps to determine the "center" of burst errors in adjacent tracks. In order to do this, the representations of the ECC blocks with errors are redrawn as an X-Y graph with the X axis as the angle and the Y axis as the radius. This is demonstrated in Figure 3-13. The bar on the right shows the full scale of colors shown, with black at the bottom showing little to no errors, and white at the top as areas with a high concentration of errors.

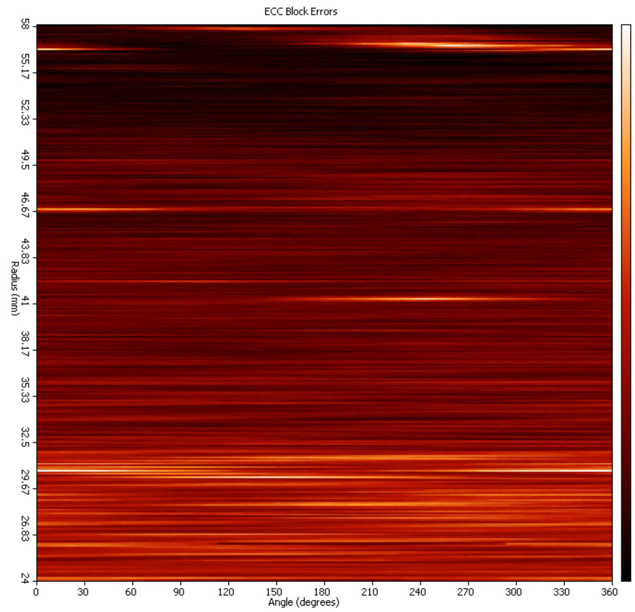


**Figure 3-13: X-Y Graph Representation of ECC Block Centers**

This graph can be interacted with in two ways to manually identify the “centers” or concentrations of ECC error blocks. The first method is to move the mouse over the ECC graph. A single ECC object is then drawn on the disc representation as an overlay at the position corresponding to the current position of the mouse on the ECC graph. This is shown in Figure 3-14. Note that the ECC object drawn as an overlay is highlighted in a similar manner to the manually observed defects which can be disabled from the ECC menu in SectorDraw.

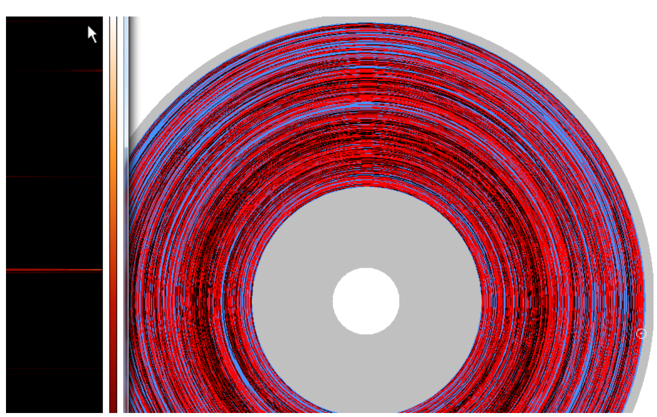

**Figure 3-14: Mouse Marking Current Position on ECC Graph**

The second method is to click a point on the ECC graph to manually mark an ECC error block "center." These centers are then drawn as objects on the disc image of SectorDraw which can be manipulated by changing rotation and transparency. The disc image with the manually identified center blocks is shown in Figure 3-15.

**Figure 3-15: SectorDraw ECC Block Center Objects**

#### 3.1.7.2.3 Digital Camera Image

After the images from the digital camera are cropped to display only the disc, these may be overlaid on top of the disc to draw comparisons between artifacts seen in the image to digital errors. This functionality is shown in Figure 3-16.

**Figure 3-16: SectorDraw Disc Image Overlay**

#### 3.1.7.2.4 Dr. Schwab Image

Similar to the digital camera image, a screenshot may be taken of the argusEco software's drawing of the measured reflectivity of the disc. When this image is cropped, it may also be shown over the disc as shown in Figure 3-17. This is referred to as the Dr. Schwab image.

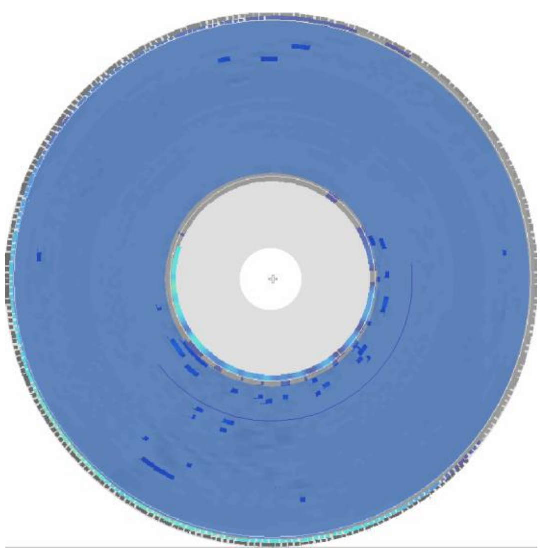

**Figure 3-17: SectorDraw Dr. Schwab Overlay**

#### 3.1.7.3 Image Sets

In order to provide ease of analysis for comparisons between digital errors and collected data over time, SectorDraw possesses the concept of image sets. If all Shuttleplex analysis files, camera images, Dr. Schwab images, and observed defect files are contained in a single folder and named correctly, SectorDraw can display each in multiple concurrent displays. This is shown in Figure 3-18.

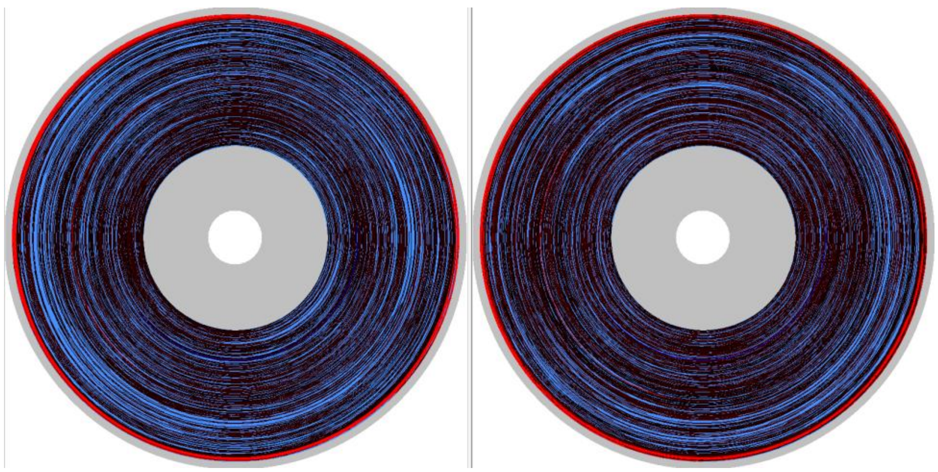

**Figure 3-18: SectorDraw Image Sets**

If a slider control is moved, the user can see the in-order progression of a single disc over time. The folder containing these files constitutes a single image set. Additionally, the rotation and transparency of each overlay may be saved in a single configuration file per set.

#### 3.1.7.4 Image Export

If a view is found to be of interest in SectorDraw, the corresponding images may be exported as an image file. The resulting image can be created from a single disc view or as a side-by-side image as shown in Figure 3-18.

## 3.2 SectorDraw Validation

In order to validate the functionality and usefulness of SectorDraw for this study, initial tests were conducted that simulated large physical defects on an optical disc. The disc was written with data, analyzed with the Shuttleplex, and marked with black spots using a permanent marker to simulate physical defects. During each step, images were also taken with the digital camera following the pattern to be described in the validation study. This section shows the steps taken in these initial tests.

### 3.2.1 Data Collection and Analysis

Using the InfraRecorder software, close to 4.7 GB of DVD movie data was written to a Taiyo-Yuden DVD-R. This brand was chosen due to the fact that it is well respected and the discs are accepted as long lasting within the industry. Experience has shown that they have fewer errors after initial writing, and they typically match or outperform archival grade DVD-Rs. The disc was then analyzed for digital errors using the Shuttleplex.

A straight line was made with a permanent marker in the center hole of the disc as an arbitrary 0° reference point. Two marks were then made on the disc using a permanent black marker. The sizes of these artificial "defects" were kept small to allow the DriveAid software to fully analyze the discs but they were large enough to cause serious errors in many adjacent tracks. The first mark was made at about 25 mm from the center of the disc at 0°, and the second mark was at roughly 52 mm and 180°. An image was taken of the disc using the digital camera and mount as discussed, and the Shuttleplex was again used to analyze the digital errors. The camera image of the disc with the two marks and reference point is shown in Figure 3-19.

**Figure 3-19: SectorDraw Validation Disc with Two Marks**

To further demonstrate the utility of SectorDraw, two additional marks were made. These are made at 90° angles from the original two marks and at differing radii. Another image was taken with the digital camera and the disc was analyzed yet again for digital errors. The camera image of the disc after further marking is shown in Figure 3-20.

**Figure 3-20: SectorDraw Validation Disc with Four Marks**

Finally, this information was compiled in SectorDraw and comparisons were made, which will be discussed in the next chapter.

### 3.3 Validation Study

In order to prove the value of the framework developed, a validation study was performed using all tools and analysis methods discussed. In this section, the data collection and analysis processes utilized will be explored.

#### 3.3.1 Data Collection

The data collection phase of the validation study involved studying DVD-Rs using the aforementioned tools as they were aged artificially. The process of analyzing the discs for digital errors, making defect observations and measurements, and twelve hours of artificial aging was considered to be a single iteration. This was repeated until the majority of the discs either failed according to the DVD-R specification as described in Section 2.2.2 or had significantly increased in error counts when compared to the initial analyses. A significant change was defined to be an increase of 200% of PIE errors or any increase in the number of POF errors. First, media preparation will be discussed. Next, the steps involved in collecting data during an iteration will be explored. Finally, the accelerated aging method will be discussed with an explanation of the conditions for the end of data collection.

##### 3.3.1.1 Media Preparation

Two brand new DVD-Rs from six brands were first selected for a total of twelve discs. These discs were either designed and marketed as archival quality or were established to perform quite well under harsh conditions. The brands chosen in the validation study were Delkin, MAM-A, Mitsubishi, Millenniata, Taiyo Yuden, and Verbatim. Each brand was assigned an abbreviation as shown in Table 3-1 and the discs were assigned numbers such as DK1, DK2, MA1, and so forth. Additionally, the discs were each marked with an arbitrary line in the center hole used as a common reference point in locating defects and in digital camera images.

**Table 3-1: Disc Brand Abbreviations**

| *Brand* | *Abbreviation* |
|---|---|
| Delkin | DK |
| MAM-A | MA |
| Mitsubishi | MI |
| Millenniata | ML |
| Taiyo Yuden | TY |
| Verbatim | VB |

Each discs was analyzed using the Dr. Schwab instrument and then written with almost 4.7 GB of DVD video data. These initial Dr. Schwab results were used as a reference point to study the change in disc reflectivity before and after writing. After writing, iteration testing on the discs began. At the beginning of the study, several discs were replaced due to various issues. These will also be discussed in this section.

#### 3.3.1.2 Iteration Measurements

The measurement steps of a single iteration consisted of analysis with the Shuttleplex for digital errors, observation of defects, analysis with Dr. Schwab, and creation of a digital camera image.

#### 3.3.1.2.1 Shuttleplex Analysis

The Shuttleplex was used to analyze each disc fully for digital errors. The naming of each analysis export file was done according to the disc name and the total number of hours it had been aged. In order to account for the initial Dr. Schwab analyses, 000 was used as the "hours aged" designation for before writing, and 001 was used for after writing even though no aging had been completed.

As the discs accumulated errors from artificial aging, at some point they began to take prolonged periods of time to analyze. This was due to the Shuttleplex software reanalyzing certain ECC blocks to obtain error counts. While a typical analysis took about 30 minutes, some analyses ran for as much as several hours to over a day when large amounts of errors were encountered. Due to the fact that this repeated reading could potentially have caused damage to the drive, a time limit was set for each analysis at 1 hour. At this point, the analysis was deemed a failure and the disc was removed from the study. In each case that this occurred, the amount of errors exceeded the threshold limits of PIE Sum 8 over 280 and POF errors as defined in the DVD specifications.

#### 3.3.1.2.2 Studying Visually Detectable Defects

Visually identifying and measuring physical defects involved a manual process of using the naked eye, eye loupes, and microscopes. First, the discs were cleaned using a can of pressured air, cotton swabs, and lint-free KimWipes™ (from Kimberly Clark®). Later, Kim wipes were used as little as possible as it was found that they tended to scratch the surface of the disc. It was for this reason that the MA1 disc was replaced with MA3. The can of compressed air also caused "frost burns" to VB1, which was then replaced with VB3. However, VB1 stayed in the study due to the clear presence of a manufacturing defect. After cleaning, the discs were then held at different angles with the data side up to manually observe any interesting features. When a feature was found, it was scrutinized by using eye loupes with varying levels of magnification. While all defects were initially catalogued and identified, many of these turned out to be of little consequence to the study. These were marks such as light scratches and surface contaminants. According to the literature, these features would have little effect on the data itself. Therefore, after initially studying all possible features, only defects that were not surface contaminants or scratches were studied.

Before the discs were artificially aged, all defects were termed manufacturing or initial defects. Afterwards, all new defects were assumed to have developed due to the aging process. The observations on manufacturing defects were still valuable to understand the initial state of the disc and their effect on digital errors, but the features of interest were largely those that developed after aging.

For all defects studied, images were taken with a microscope. These images were used to create the defect files for SectorDraw. Many parameters were recorded during this process: unique number, location on disc, size, classification, and type.

#### 3.3.1.2.2.1 Unique Number

Defects were assigned a unique number according to each disc, and these numbers were used to track the defects throughout the study.

#### 3.3.1.2.2.2 Location on Disc

Radius and angle were measured by overlaying a transparency with measurement information on the disc. The figure used to create this template is shown in Figure 3-21. Radial measurements were recorded to be precise within 0.5 mm, and angle measurements were recorded within 2° of the actual value.

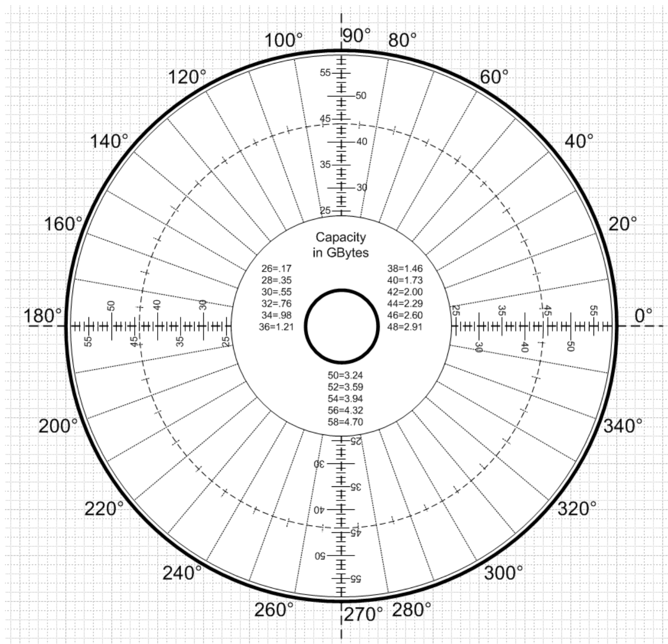


**Figure 3-21: Measurement Transparency**

#### 3.3.1.2.2.3 Size

Width and height were measured using the images from the microscope. Each image was overlaid with a grid of known dimensions and sizes were calculated roughly from these. The maximum size recorded during this process was 1000 um, and the only features that were above this limit were typically surface contaminants and scratches. A rotation for each defect was also calculated for SectorDraw.

#### 3.3.1.2.2.4 Classification

The defects were classified by the layer of disc that they resided in or on. There were three layers of concern: the surface of the disc on the data side, the polycarbonate, and the reflective material. The defects were determined to be in a certain classification by studying the microscope images for patterns and the relative depth of the reflections. It was initially determined that the features on the surface would display two reflections in images, those in the polycarbonate would display only one reflection, and those on the reflective layer would display no reflections. This is shown in Figures 3-22, 3-23, and 3-24 for defects at the surface, polycarbonate, and reflective layers respectively. The first is a piece of dust which clearly resided on the surface of the disc. The second was an injection flaw in the polycarbonate formed during the manufacturing process, and the third was a particle on the reflective layer.

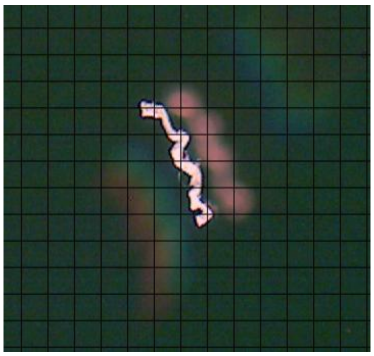

**Figure 3-22: Dust Particle On Disc Surface**

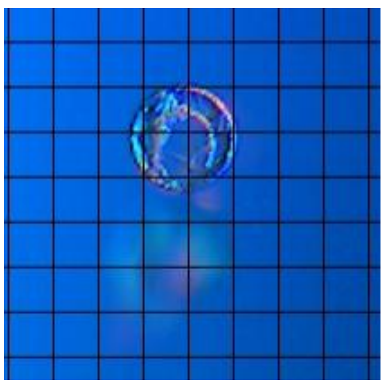

**Figure 3-23: Injection Flaw in Disc Polycarbonate**

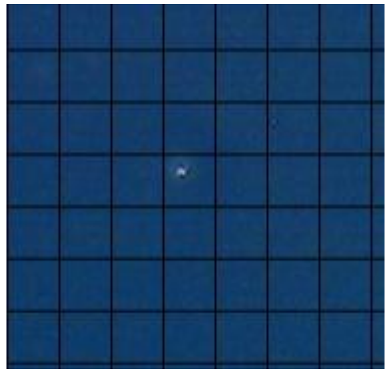

**Figure 3-24: Particle on Disc Reflective Layer**

#### 3.3.1.2.2.5 Type

Finally, the actual physical type of each defect was determined. These included injection flaws, inclusions, scratches, surface contaminants, and pinholes.

### 3.3.1.2.3 Dr. Schwab Analysis

Analysis was performed on the Dr. Schwab instrument for each disc. This tool had different sets of parameters that could be used in the analysis. For this study, parameter set 57, "DVD-R single layer finished," was used as this correctly represented the type of discs being analyzed. The analysis file produced then was read in the argusEco software and a screenshot of the image of disc reflectivity was taken as previously mentioned. This image was cropped, named the same as the analysis file with a specific ending, and used in SectorDraw.

In order to verify the repeatability of the Dr. Schwab analyses, three measurements were taken for each disc in the study. These were then averaged, and a maximum percentage error and actual maximum difference was calculated. The results are shown in Table 3-2. The maximum calculated percentage error was 0.557%; this was well below the level needed to prove repeatability of the measurements. Thereafter, only one measurement was taken for each disc per iteration.

**Table 3-2: Dr. Schwab Repeatability Results**

| *Test 1* | *Test 2* | *Test 3* | *Average* | *Maximum Percentage Error* | *Maximum Difference* |
|---|---|---|---|---|---|
| 52.11947 | 52.38707 | 52.12456 | 52.21037 | 0.338% | 0.177 |
| 51.89480 | 51.85375 | 51.86092 | 51.86982 | 0.048% | 0.025 |
| 50.88110 | 50.88643 | 50.92380 | 50.89711 | 0.052% | 0.027 |
| 50.58085 | 50.52315 | 50.59854 | 50.56751 | 0.088% | 0.044 |
| 50.55641 | 50.65146 | 50.68972 | 50.63253 | 0.150% | 0.076 |
| 61.96201 | 62.05335 | 61.99797 | 62.00444 | 0.079% | 0.049 |
| 45.40544 | 45.25294 | 45.48039 | 45.37959 | 0.279% | 0.127 |
| 30.15029 | 30.17129 | 30.14832 | 30.15663 | 0.049% | 0.015 |
| 30.25473 | 30.33465 | 30.34342 | 30.31094 | 0.185% | 0.056 |
| 63.73337 | 63.70111 | 63.70171 | 63.71206 | 0.033% | 0.021 |
| 63.87679 | 64.00079 | 64.03823 | 63.97194 | 0.149% | 0.095 |
| 43.02647 | 43.14614 | 43.09411 | 43.08891 | 0.145% | 0.062 |
| 61.11832 | 60.67558 | 60.54532 | 60.77974 | 0.557% | 0.339 |
| 60.54295 | 60.80677 | 60.56181 | 60.63718 | 0.280% | 0.170 |
| | | | ***Maximum*** | 0.557% | 0.339 |

#### 3.3.1.2.4 Digital Camera Image

The camera used was an HP Photosmart R507 (4.1MP). In order to obtain an optimal image, several default settings of the camera were changed. EV Composition was set to 1.0, macro mode was enabled, and the flash was turned off. A ten second timer was also used to prevent the camera from shaking. The side flood lights were used and the other lights in the room were turned off to eliminate extra glare. After initial pictures were taken during the first iteration, silk material was placed in between the flood lights and the disc to disperse the glare on the disc.

### 3.3.1.3 Accelerated Aging

The final step of an iteration consisted of aging the discs artificially using the environmental chamber. A profile was created with the following steps:

1. Elevate temperature to 85° F and 85% humidity over 15 minutes
2. Hold temperature and humidity at 85° F and 85% for 12 hours
3. Ramp down temperature and humidity to 20° F and 20% respectively over 20 minutes

The light was also turned on at the beginning of the profile and turned off at the end. The discs were then left in the chamber for about three hours in order to prevent additional damage from environmental acclimation.

Due to adhesive separation issues with the Millenniata discs and high humidity in the first iteration aging, ML1 was taken out of the study as it would no longer analyze successfully. Two additional M-DISCs were prepared, studied, and aged again at 85° C and 85% to have two working M-DISCs that had been exposed to the same conditions as the other discs. All subsequent accelerated aging was completed with the temperature and humidity decreased from 85° C and 85% to 80° C and 80% in order to prevent the same issues from occurring.

#### 3.3.1.4 Conditions for End of Tests

The final condition of the discs was that many of them had encountered a significant increase in the quantity and value of errors they possessed according to the Shuttleplex analysis. In most cases, this meant that they had error counts greater than the DVD-R specifications. This was defined as a PIE Sum 8 value greater than 280 or a single POF error or more present in the disc. In the end, three iterations were completed before the majority of discs reached this point. In all, nine discs significantly increased in errors and were included in the full analysis utilizing SectorDraw. Two of these did not go through all three iterations, as they failed to analyze using the Shuttleplex after only two iterations. The complete list of DVDs along with their initial and final PIE 8 max and POF max error counts are shown in Table 3-3. The bold rows mark the discs selected for the final analysis.

**Table 3-3: Error Values and Iterations of All Discs**

| *Disc* | *Total Iterations* | *Initial PIE 8* | *Final PIE 8* | *Initial POF* | *Final POF* |
|---|---|---|---|---|---|
| DK1 | 3 | 463 | 759 | 0 | 0 |
| DK2 | 3 | 456 | 596 | 0 | 0 |
| **MA1** | **3** | **158** | **1683** | **0** | **134** |
| MA2 | 3 | 203 | 499 | 0 | 0 |
| MA3 | 3 | 199 | 379 | 0 | 0 |
| **MI1** | **3** | **30** | **1917** | **0** | **3** |
| **MI2** | **3** | **20** | **1186** | **0** | **1** |
| **ML3** | **2** | **367** | **996** | **0** | **172** |
| ML4 | 3 | 359 | 556 | 0 | 0 |
| **TY1** | **3** | **64** | **441** | **0** | **0** |
| **TY2** | **3** | **116** | **687** | **0** | **0** |
| **VB1** | **2** | **38** | **120** | **0** | **0** |
| **VB2** | **3** | **52** | **2362** | **0** | **127** |
| **VB3** | **3** | **69** | **2314** | **0** | **61** |

### 3.3.2 Data Analysis

After all data was gathered from each iteration, image sets were created for SectorDraw. All analysis files, defect files, digital camera images, and Dr. Schwab images were placed into a single directory for each disc. SectorDraw configuration files were created to include information for each iteration including the initial iteration where certain information was present but not a Shuttleplex analysis file. Each image produced by SectorDraw in the set represented a single iteration.

In analyzing the data, the digital errors were compared individually to the manually observed defects, digital camera images, Dr. Schwab images, and concentrated ECC error block centers. It should be noted that while no algorithm was present to compare the ECC block centers and defects, visual comparison served as a well suited inspection tool. A scale with associated criterion was developed in order to understand and rank the utility and ease of use of each aspect of the framework. A separate set of criteria was developed as well in order to rate the effectiveness of each DVD error type as reported by the Shuttleplex analysis. These ratings and rankings were used to identify the process with which digital errors could be linked with physical defects. Finally, the identified process was used to create several examples establishing the validity and utility of the framework as a whole. These results will be discussed next.

# 4 RESULTS AND ANALYSIS

The validation of the developed framework was the primary focus of this study. As mentioned, no statistical analysis or cataloguing was undertaken to understand all types of physical defects or their full relationship to digital errors. Instead, measurements were developed to quantify the utility of each aspect of the framework itself. From these results, the most useful portions of the framework were identified and these were then used to gather several examples of the relationships between defects and digital analyses. This chapter contains the results and analysis of the initial SectorDraw validation study, the measurements developed, the collected examples, and the overall analysis.

## 4.1 SectorDraw Validation

The initial validation study conducted with SectorDraw proved to be very successful in establishing the effectiveness of the tool. This section is divided into results and analysis of the validation.

## 4.2 Validation Results

The results for the initial error analysis, two marks, four marks, and utilizing ECC block centers are discussed in this section.

### 4.2.1 Initial Analysis

Once the analysis file was loaded in SectorDraw, it produced an image as shown in Figure 4-1. This image displayed the POF error type, with blue tracks signifying no errors and red tracks the opposite. Note that this image showed no POF errors on the disc, which was to be expected from a freshly written disc of high quality. POF errors on new discs would likely mean that something in the manufacturing process was causing unrecoverable errors on discs.

**Figure 4-1: Initial SectorDraw POF Error Representation**

For reference, Figure 4-2 shows the PIE errors for the same disc and the same Shuttleplex analysis file. Notice that errors covered the majority of the disc, with only minor areas of blue showing through. This is again typical of a freshly written disc and highlights how many random errors are present on a disc.

**Figure 4-2: Initial SectorDraw PIE Error Representation**

### 4.2.2 Two Marks

After the first two marks were made on the disc as discussed in Chapter 3, the resulting disc image from the digital camera was overlaid on the digital error representation of PIE errors in SectorDraw. It was immediately apparent that the amount or intensity of error values were greater in the same radial band that the mark resided in, as seen in Figure 4-3 by the brighter red bands of errors. These errors matched almost perfectly with the inner mark, shown at about 315°, and quite well with the outer mark, shown at 135°. In this and all subsequent figures, the marks have been rotated to what was assumed to be the closest matching arrangement with the digital errors. This was done by visual inspection based on the width, frequency, and intensity of the errors.

**Figure 4-3: Two Mark Disc Image Overlaid on PIE Errors**

The same results were observed using the POF error representation, as shown in Figure 4-4. POF errors are unrecoverable data errors, therefore they are fewer in number and in value. The inner mark again matched the radial band of the errors, but the outer mark seemed to just touch the ECC block with errors. The marks in this figure are shown at about 45° and 225°.

**Figure 4-4: Two Mark Disc Image Overlaid on POF Errors**

### 4.2.3 Four Marks

The results of adding two more marks to the disc for a total of four were extremely revealing as to the relationship between digital errors and physical defects. With four total marks on the disc at 0°, 270°, 90°, and 180°, the analysis with SectorDraw showed four separate radial bands of increased error counts for the PIE error type. These radial bands again matched the radial size and location of the marks made on the disc, as shown in Figure 4-5.

**Figure 4-5: Four Mark Disc Image Overlaid on PIE Errors**

Figure 4-6 shows the same results utilizing the POF error type. Interestingly, it appeared that the outer error showed in Figure 4-4 disappeared in the newer analysis file representation. This will be explored later in section 4.3.1.

**Figure 4-6: Four Mark Disc Image Overlaid on POF Errors**

### 4.2.4 ECC Block Centers

As discussed in Chapter 3, determining the angular position of a certain defect presents many unique challenges. For this reason, the ECC block center graph of SectorDraw was utilized to determine the angle of the marks. This graph is shown in Figure 4-7 for two marks and 4-8 for four marks.

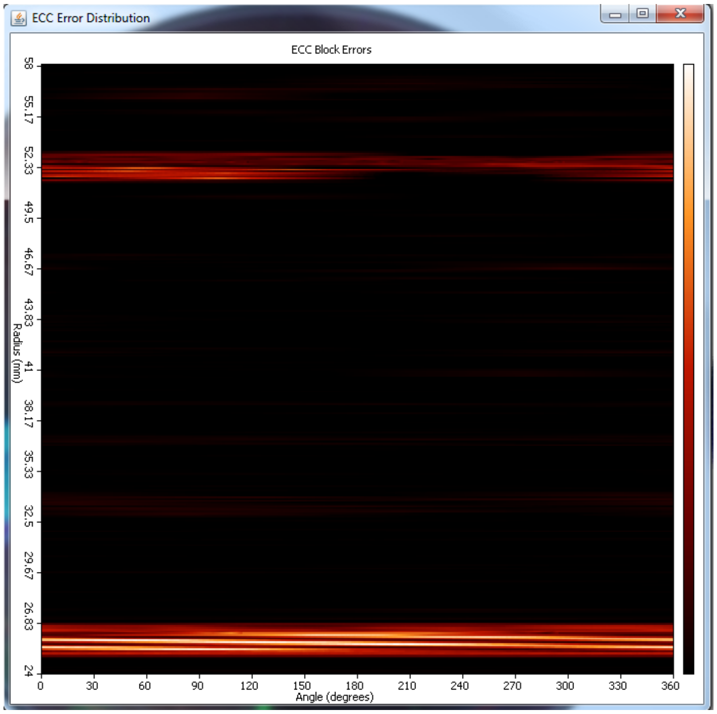


**Figure 4-7: Two Marks ECC Block Center Graph**

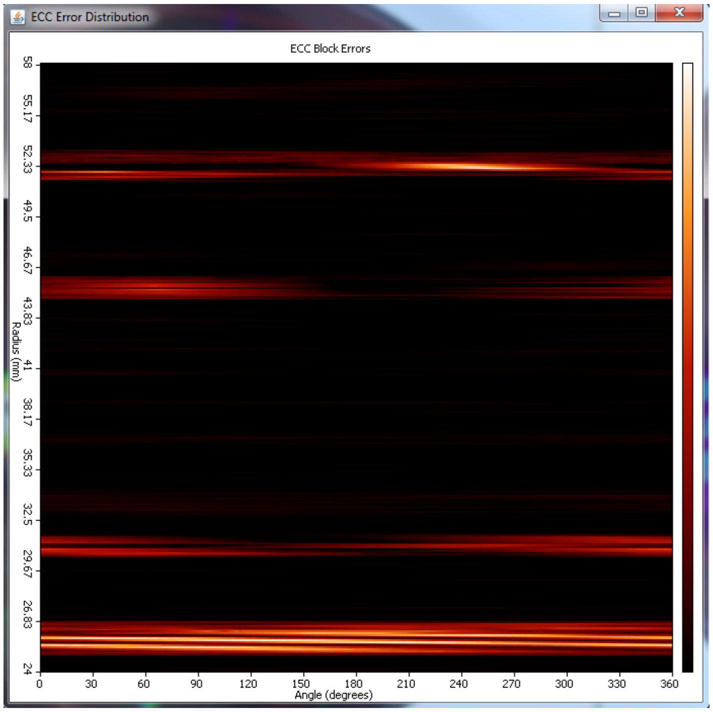


**Figure 4-8: Four Marks ECC Block Center Graph**

From the graphs, the bands matched precisely with the number of marks on the disc. Using these graphs and visual inspection, the angular and radial locations were determined as shown in Table 4-1 for two marks and Table 4-2 for four marks. The tables show the radius, degrees from the arbitrary 0° reference point, estimated degrees from the ECC block center graphs, and the difference between these angles for each mark. They also show the calculated average degree offset as the position that best matches all defects.

**Table 4-1: Two Marks Locations**

| *Radius* | *Degrees* | *Estimated Location* | *Difference* |
|---|---|---|---|
| 25 | 0 | 180 | 180 |
| 52 | 180 | 60 | 240 |
| | | **Best Offset** | 210 |

**Table 4-2: Four Marks Locations**

| *Radius* | *Degrees* | *Estimated Location* | *Difference* |
|---|---|---|---|
| 25 | 0 | 60 | 60 |
| 30 | 270 | 330 | 60 |
| 45 | 90 | 65 | -25 |
| 52 | 180 | 250 | 70 |
| | | **Best Offset** | 60 |

Rotating the marks in the disc view with the disc image overlay to these angles resulted in Figures 4-9 and 4-10 for two marks and four marks respectively.

**Figure 4-9: Two Marks ECC Block Center Result**

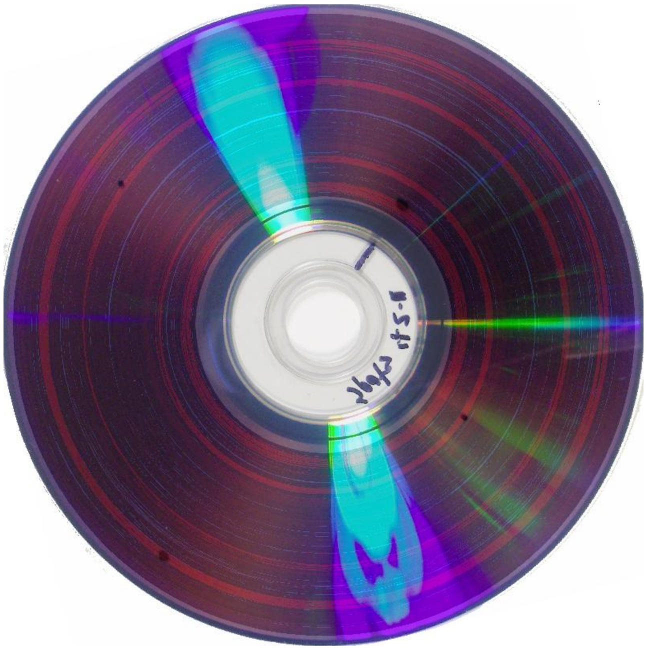

**Figure 4-10: Four Marks ECC Block Center Result**

### 4.3 Validation Analysis

The analysis of results consists of a review of the mark experiments, the ECC block center results, and conclusions.

#### 4.3.1 Mark Experiments

The errors observed in Figure 4-2 are a representation of the typical errors present on any disc due to the laser reading process. These errors, while at first glance appearing serious, were not enough to render the disc unreadable or to cause unrecoverable errors in the data due to the error correction algorithm. After the first two marks were made, however, the random errors appeared relatively less intense than the errors caused by the artificial defects. Bands of errors appeared for each defect marked. These bands corresponded almost precisely to the marks made both in position on the disc and in radial size.

Although most of the comparisons between the marks and the generated image of the digitally detected errors showed significant similarities, it is important to note that some discrepancies existed. More specifically, the marks did not always overlap with the bands of digital errors precisely, often covering areas where few or no digital errors were displayed. This is most likely due to either the difficulties of SectorDraw attempting to draw thousands of tracks in the inherently limited pixel model of the Java drawing API or a mismatched overlay of the disc image itself. Although the exact reason remains unknown, on avenue of research that should be investigated further is that of improper cropping of the disc image.A change in the manual cropping process of the disc image may solve this problem.

Another point to note is the comparison between Figures 4-6 and 4-4. In the latter, the ECC block with the POF error disappeared near the outer mark. This was unsurprising and, in fact, expected due to the random nature of DVD read errors as explained in Chapter 2. In this case, it was an assumption that the marks actually caused more errors than could be recovered from using ECC, and therefore POF errors would be present on every read of the disc. From the data gathered, however, it is apparent that the outer marks did not cause enough interference to the reading laser to cause this behavior. Larger marks or defects, especially those that exist along a single set of tracks, would cause these facts to be more prevalent. In other words, the outer marks made were most likely too small to cause POF errors on each read.

### 4.3.2 ECC Block Centers

Due to the large angular length covered by each ECC block as well as the lack of a common reference point, the exact location of the marks was difficult to determine angularly when overlaid on the digital errors. As discussed, the radii of the marks matched up with the radii of the tracks with the majority of errors. Deciding at which angle the mark was positioned, however, presented a much more complex problem. In addition to the fact that a single ECC block can cover over half the disc angularly, there was no common reference point for the beginning of the disc, or a 0° angle, except for the arbitrary mark made with a permanent marker in the center hole. These factors made it very difficult to find the exact angle of the mark when only looking at the digital errors. The problem was compounded near the center of the disc as the ECC blocks were longer angularly. Some tracks which contained errors started at the mark, others ended at the mark, and still others contained the mark somewhere inside of them. By logical deduction, it is believed that if these error-filled tracks were statistically analyzed, the result would show that the relative "center" of the ECC blocks would be precisely on the mark or defect. This assumption formed the basis of the development of the ECC block center graph feature of SectorDraw.

Utilizing the ECC block center graph in this validation proved to be useful in obtaining more specific results and in demonstrating the effectiveness of the feature itself. Decisions on the placement of the marks angularly as well as radially were able to occur due to the graphs provided by SectorDraw. While differences still existed for angular location for each mark as shown in Tables 4-1 and 4-2, confidence in correct positioning of each mark increased drastically when utilizing this SectorDraw feature.

Finally, it is important to note that the results showed a different alignment from one image to another with respect to the arbitrary 0° marked. Figures 4-9 and 4-10 are each aligned to match the digital bands of errors with the respective marks, but in each case the arbitrary 0° appeared to switch positions. At the very least, this demonstrates an additional layer of complexity that the reference point changes through each iteration of digital analysis with the Shuttleplex. If this was not the case, the arbitrary 0° marked in the center of the disc would have stayed the same between these two images. It was assumed at the beginning of the validation experiments that although the errors analyzed may change, a disc possessed a singular location for its first ECC block whose start could then be termed the 0° mark. Inherent in this assumption was that this position would not change when another analysis was completed. It is acknowledged that the problem may actually lie in how the results are outputted by the DriveAid software on the Shuttleplex, and not with the base assumption itself. The true reason is unknown, however, and will require further research outside the scope of this research to determine if it is the standard or an exception.

### 4.3.3 Conclusions

The initial SectorDraw validation proved to be a success. The software demonstrated the ability to map physical marks, or artificial defects, to digital errors obtained through the

Shuttleplex DriveAid analysis. Radial position was able to be determined correctly by utilizing the disc image overlay and the error analysis. Although determining angular position proved more difficult, it was facilitated by the generated ECC block center graphs. In the end, SectorDraw was shown to have all the features required to successfully study the relationship between physical defects and digital errors. More importantly, however, the validation provided essential information to understand the fundamental difficulties in studying the physical to digital relationship. Angular positioning was shown to be the most difficult aspect of the entire study, which proved to be true for the larger study completed with actual defects and artificial aging.

## 4.4 Measurements

In order to quantify the utility of each aspect of the framework and to identify the most effective parts, measurements were developed. Two major divisions were taken into account when creating the criteria: the ECC error types and the actual aspects of the framework itself. These are both explained fully, including results, in this section.

### 4.4.1 Error Types

As explained in Chapter 2, the error correction algorithms on a DVD utilize several error types in order to report the current status of errors on the disc. Some of these types are more useful than others, and it was explained previously that PIE 8 max, POF average, and PIF Bytes max have been shown to provide the most unique information. However, SectorDraw was not designed to highlight max and average values and instead was intended to show specific values of errors for each block. Therefore it was necessary to determine the error types that presented the most useful information for this analysis. The measurements that were developed to rank the error types and results are explored further here.

#### 4.4.1.1 Measurements

Two comparison grids were developed for quantifying the utility of the error types. The first took several criteria, explained later, into account to give a rating between 1 and 5 inclusive which compared the error types for each disc overall. A rating of 1 signified that the error type was not very useful, and a rating of 5 signified that the error type was highly useful. Another grid was constructed using the same 5-point scale which rated each error type with the average from the first grid combined with an individual rating for each criterion specifically. An important distinction to make is that these ratings were not relative as a whole, meaning that if none of the error types provided enough unique information for a single criterion, none of them would receive a 5 rating.

Only the error types mentioned in the literature as providing unique information as well as any noted as providing useful information during the analysis process were included in the scales. The final list of error types included in the ratings was POF, PIF, PIF Bytes, PIE, and PIE 8.

The criteria used in the comparisons were chosen to reflect the utility of an error type in the different use cases of SectorDraw. While by nature these criteria could be rated subjectively, every effort was made to rate based on objective data. The criteria rubric used in determining each rating is given in Appendix A, and the general questions asked in judging each criterion is given as follows.

##### 4.4.1.1.1 Disc View

In the SectorDraw disc view, how much useful and unique information did the error type provide to identify localized concentrations of errors?

#### 4.4.1.1.2 ECC Block Center Graph

In the SectorDraw ECC block center graph, how much useful and unique information did the error type provide to identify localized concentrations of errors?

#### 4.4.1.1.3 Comparisons to Defects

Regardless of the view used, how much unique information did the error type provide that matched radially and angularly with observed defects?

#### 4.4.1.1.4 Data Over Time

Did the utility of the information provided by the error type stay consistent through the iterations? Was the information provided by the error type useful in all of the iterations or only in one or two?

### 4.4.1.2 Results

The results of the comparisons are shown in Tables 4-3 and 4-4.

**Table 4-3: Error Type Comparison by Disc**

| | *POF* | *PIF* | *PIF Bytes* | *PIE* | *PIE 8* |
|---|---|---|---|---|---|
| MA1 | 5 | 1 | 2 | 5 | 2 |
| MI1 | 4 | 1 | 1 | 5 | 2 |
| MI2 | 4 | 1 | 1 | 5 | 3 |
| ML3 | 5 | 1 | 2 | 5 | 2 |
| TY1 | 1 | 1 | 1 | 5 | 1 |
| TY2 | 1 | 1 | 1 | 4 | 3 |
| VB1 | 4 | 1 | 1 | 4 | 3 |
| VB2 | 4 | 1 | 1 | 5 | 3 |
| VB3 | 4 | 1 | 2 | 5 | 2 |
| **Average** | 3.56 | 1.00 | 1.33 | 4.78 | 2.33 |
| **Rank** | 2 | 5 | 4 | 1 | 3 |

**Table 4-4: Error Type Comparison by Criteria**

| | *Disc View* | *ECC Block Graph* | *Defect Comparisons* | *Data Over Time* | *Disc Average* | ***Total Average*** | ***Rank*** |
|---|---|---|---|---|---|---|---|
| POF | 4 | 5 | 4 | 5 | 3.56 | 4.31 | 2 |
| PIF | 1 | 1 | 1 | 1 | 1.00 | 1.00 | 5 |
| PIF Bytes | 2 | 1 | 1 | 1 | 1.33 | 1.27 | 4 |
| PIE | 3 | 5 | 5 | 4 | 4.78 | 4.36 | 1 |
| PIE 8 | 2 | 2 | 2 | 4 | 2.33 | 2.47 | 3 |

Both comparisons agree on the rank of each error type exactly. PIE was measured as the most useful error type with POF close behind. PIE 8 was shown to be useful in some situations but not all, and PIF Bytes and PIF provided almost no information independent from any error types. Both showed identical information to the POF error type. Points to note on the comparisons above include the 5 rating for PIE and POF in the ECC block center graph view and the 5 and 4 for the same error types under the defect comparisons criterion. These were identified as the most useful views to use for the error types. PIE 8 was shown to be useful in rare situations for both the disc view and the ECC block center graph, but overall did not supply much useful information. Typically the PIE 8 disc views and ECC block center graphs displayed most of the disc covered in errors which did not allow localized errors to be identified.

As discussed previously, these ratings were not relative as a whole and therefore at least two of the five error types proved highly useful to fulfill the goals of the framework. Perhaps even more important than the quantities given above, the results precisely matched observations made during the analysis phase of the study. This attests to the reliability of the gathered data.

### 4.4.2 Framework Aspects

The framework was divided into different aspects reflecting its features, data, and process. The aspects chosen specifically to study included the SectorDraw regular disc view, the ECC block center graph, the digital camera image and overlay, the Dr. Schwab image and overlay, the manually observed defects and overlay, and other SectorDraw features. This last category was created to account for smaller aspects of the framework and consisted of the rotation and transparency control of overlays, image sets, zooming and panning abilities, and configuration files. The scales, criteria, and results for each aspect are discussed in this section.

#### 4.4.2.1 Measurements

Each aspect was rated by specific criteria on the same 5 point scale as the error types, with 1 signifying not very useful, and 5 signifying highly useful. Again the ratings were not relative as a whole and therefore could be taken at face value for a measurement of utility. The criteria and the comparison itself both differed from the error type comparisons. A large comparison matrix was created which contained a rating for each aspect for a certain disc and a certain criteria. While most of these ratings were completed individually, some were static no matter which disc was used. These will be noted later on. The criteria rubric used for each rating is given in Appendix A and the general questions asked to guide the ratings were as follows.

##### 4.4.2.1.1 Identifying Localized Errors

How much useful information was provided by the aspect of the framework to identify localized concentrations of errors?

#### 4.4.2.1.2 Physical to Digital Connection

How much useful information was provided by the aspect of the framework to establish a connection between the physical and digital data?

#### 4.4.2.1.3 Data Over Time

Did the information provided by the aspect of the framework change in each iteration or did it remain static? Did the information provided by the aspect of the framework increase in utility through the iterations?

#### 4.4.2.1.4 Ease of Use and Viewing

How readily visible was the information provided by the aspect of the framework? How quick was the process to make observations based on the information provided by the aspect of the framework? How easy was it to make use of the information provided by the aspect of the framework?

#### 4.4.2.1.5 Ease of Gathering Information

How easy was the data able to be gathered in order to use the aspect of the framework?

### 4.4.2.2 Results

The averages and ranking of each aspect are shown in Table 4-5.

**Table 4-5: Framework Aspect Comparison Results**

| | *Disc View* | *ECC Block Centers* | *Camera Images* | *Dr. Schwab Images* | *Defects* | *SectorDraw Features* |
|---|---|---|---|---|---|---|
| Identifying Localized Errors | 2.22 | 4.33 | 2.44 | 1.00 | 5.00 | *1.00* |
| Physical-Digital Connection | 3.22 | 3.56 | 2.33 | 1.00 | 4.00 | *5.00* |
| Data Over Time | 3.89 | 4.33 | 1.22 | 1.33 | 4.33 | *5.00* |
| Ease of Use | *3.00* | *1.00* | *5.00* | *5.00* | *5.00* | *5.00* |
| Ease of Gathering | *3.00* | *5.00* | *2.00* | *1.00* | *1.00* | *5.00* |
| **Average** | 3.06 | 3.51 | 2.60 | 2.00 | 3.83 | 4.10 |
| **Rank** | 4 | 3 | 5 | 6 | 2 | 1 |

The cells in italics were static ratings across all discs as discussed previously. From the resulting table, it is clear that SectorDraw's features proved absolutely essential to the utility of the framework. The reason for this is that these features were utilized in every single comparison made throughout the measurements. While some were used more than others, such as controlling rotation and transparency and image sets, all were utilized at one point or another in almost every comparison.

Although decidedly difficult to gather data for, the defects and associated overlay also were shown to be invaluable to the framework. The fact that ECC block center graphs were in the third position in rank was not surprising after making doing initial analysis with SectorDraw, but would have been very surprising during the development of the framework. It was not expected that the graphs would become a vital tool in identifying localized errors. The only reason why it was not ranked higher was due to the steps required to use this feature, including generating the graph and visually inspecting it for center points. SectorDraw's disc view also was shown to be quite useful for showing how the data changed over time and for making the physical to digital connection.

Unfortunately, the image overlays, including those for the digital camera images and Dr. Schwab images, resulted in very little useful information. Although extremely useful in the initial SectorDraw validation discussed previously, actual defects were shown to be too small for the digital camera images to display any useful information about them. The Dr. Schwab image appeared in most cases to change after writing of the disc and then stay relatively static throughout all subsequent iterations. In both cases, it was assumed that they would present useful information to explain failure reasons beyond defects, but this assumption was erroneous.

Finally, just as with the error type measurements, the results matched precisely with general observations made during the analysis of the data. This again gives credence that the scales and criteria used were well fitted to objectively measuring the utility of the aspects of the framework.

### 4.5 Examples

The data used in measuring the utility of each aspect of the framework was also employed to construct a grid comparing each disc to the others with the same five criteria. The average rating was calculated for each criterion and disc, and an overall average rating was then calculated for each disc. The discs were then ranked based on the overall average, as shown in Table 4-6. If any discs possessed the same average, they were assigned the same rating.

**Table 4-6: Disc Rating Results**

| | *MA1* | *MI1* | *MI2* | *ML3* | *TY1* | *TY2* | *VB1* | *VB2* | *VB3* |
|---|---|---|---|---|---|---|---|---|---|
| Identifying Localized Errors | 2.50 | 3.17 | 3.00 | 2.17 | 3.00 | 2.33 | 2.67 | 2.67 | 2.50 |
| Physical-Digital Connection | 3.17 | 3.50 | 3.50 | 1.83 | 3.67 | 2.83 | 3.83 | 3.17 | 3.17 |
| Data Over Time | 3.67 | 4.00 | 3.67 | 2.50 | 3.17 | 3.17 | 3.67 | 3.00 | 3.33 |
| Ease of Use | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Ease of Gathering | 2.83 | 2.83 | 2.83 | 2.83 | 2.83 | 2.83 | 2.83 | 2.83 | 2.83 |
| **Average** | 3.23 | 3.50 | 3.40 | 2.67 | 3.33 | 3.03 | 3.40 | 3.13 | 3.17 |
| **Rank** | 5 | 1 | 2 | 9 | 4 | 8 | 2 | 7 | 6 |

This table reveals the discs that were the most well-suited to make use of the framework in order to demonstrate relationships between digital errors and physical defects. Due to this data, MI1, MI2, and VB1, the three highest rated discs, were chosen to serve as examples of the functioning framework. These were considered sufficient to achieve the objective of validating the framework. It should also be noted that these discs were identified for this purpose from individual results obtained during the collection of the data. In other words, the calculated data matched observations made during the course of the study. In this section, the analysis completed on each of these discs with the error types and aspects of the framework identified as the most useful will be presented.

### 4.5.1 MI1

The MI1 disc exhibited the formation of large abnormalities in the disc which were able to be correlated with digital errors. Although almost no defects were observed before and after writing, the first 12 hours of artificial aging began to reveal black spots along the outer edge of the disc. After 24 hours in the environmental chamber, these spots were clearer and more numerous, as shown in Figure 4-11.

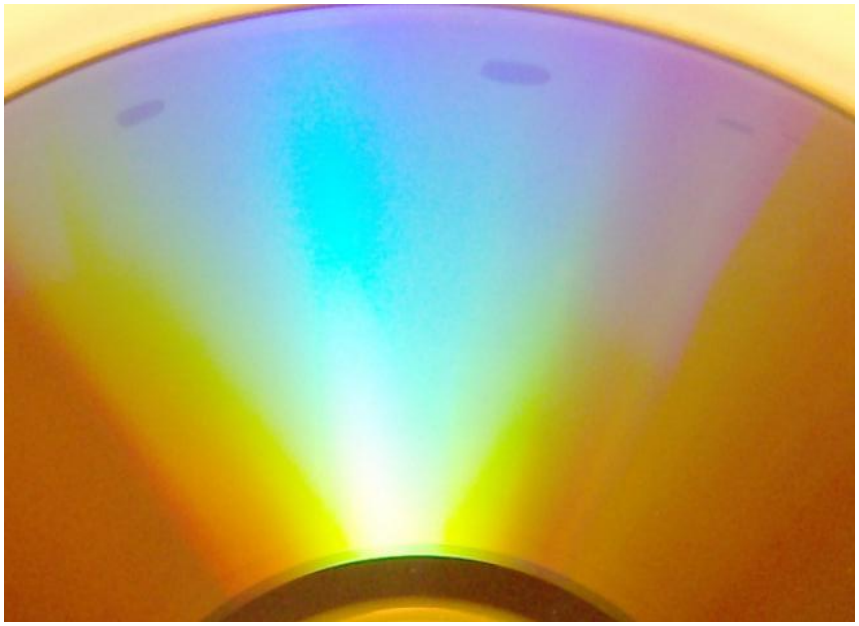

**Figure 4-11: MI1 Black Spot Defects at 24 Hours**

Six total spots were observed, ranging from 150um by more than 1mm to well over 1mm by 2mm. Every defect resided within the radii of 54.5mm to 55.5mm. From the data collected as discussed in the Measurements section, POF and PIE error types were utilized in combination with the disc view, the ECC block center graph, the manually observed defects, and the digital camera image to study the physical to digital relationships. First, the ECC block center graph was generated for POF errors for the 24 hour iteration as shown in Figure 4-12. This was the first iteration that POF errors appeared on the disc.

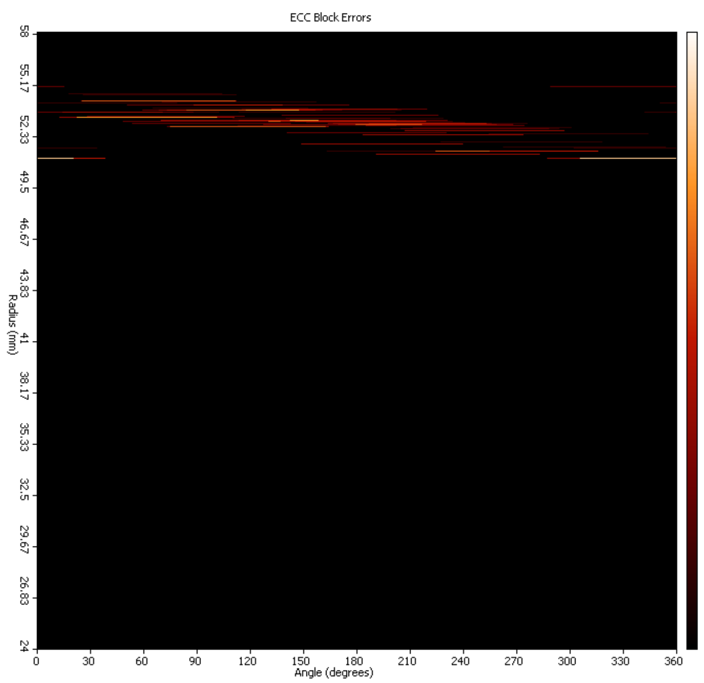


**Figure 4-12: MI1 POF at 24 Hours ECC Block Center Graph**

The graph shows many potential localized error concentrations, all between 50mm and 55mm. At first glance, it would appear that the black spot defects, lying in the angular band near 55mm, would match with this graph at around 90°-120°. However, making this adjustment on the disc view resulted in the image shown in Figure 4-13.

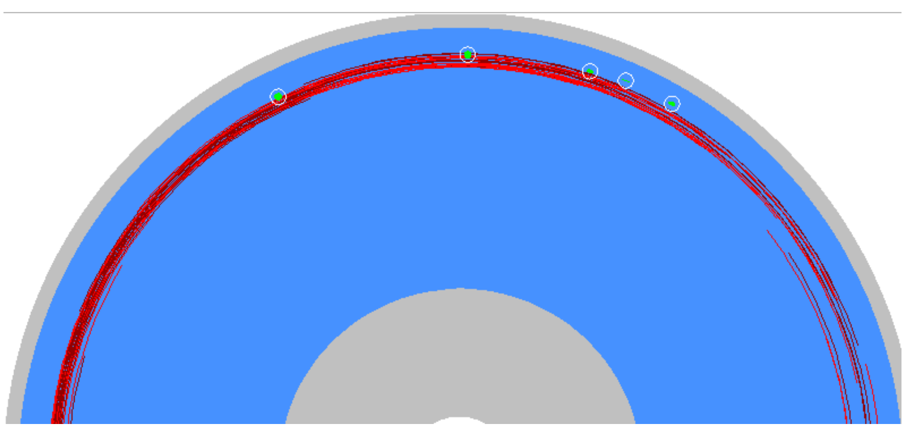

**Figure 4-13: MI1 POF at 24 Hours with Adjusted Defects**

As can be observed, the radius does not match with the bands of defects very well at this position. Rotating the defects in the disc view to match with the radius of the error filled ECC blocks resulted in an image that did not match with what was expected. The defects were at the correct radius, but were in an angular band that did not contain many errors as the other half of the disc, as shown in Figure 4-14.

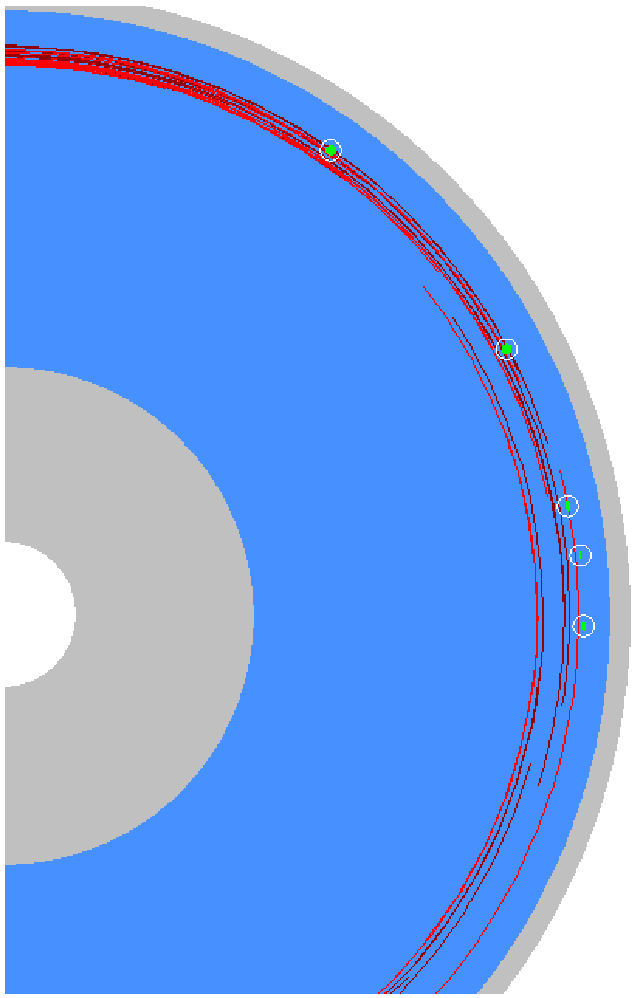

**Figure 4-14: MI1 POF at 24 Hours with Defects Matching Radial Bands**

It is expected that the process to manually measure the radius of the defects is at fault in this situation. Most likely, the defects were actually related to the numerous errors near 270°, or the furthest right edge of the disc, shown in Figure 4-13. The MI1 disc was unique in that it was one of the only discs to possess defects large enough to be seen in the digital camera image. Unfortunately, this overlay showed the same results as the manually observed defect measurements and thus presented little useful information. An example of this can be seen in Figure 4-15 where the disc image has been rotated to a similar angle as that of Figure 4-14.

**Figure 4-15: MI1 POF at 24 Hours with Digital Camera Image**

Using the PIE error type, the disc view showed large differences between all iterations compared to the final one at 24 hours. This can be observed in Figures 4-16 and 4-17.

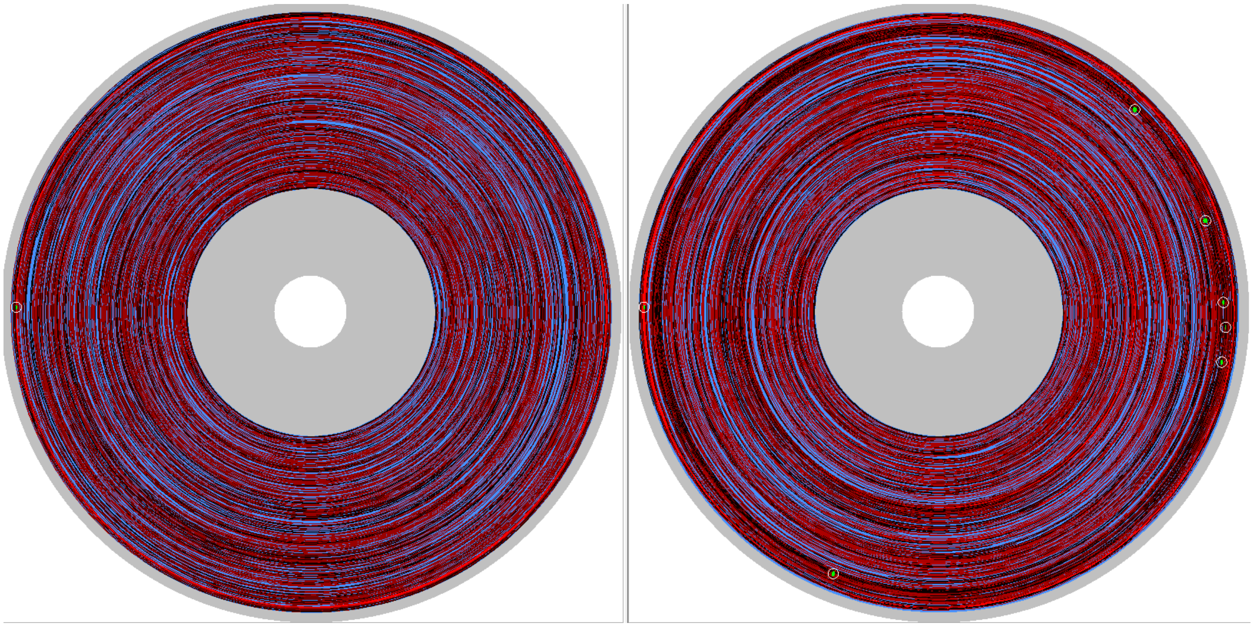

**Figure 4-16: MI1 PIE Comparison of Initial vs 12 Hours**

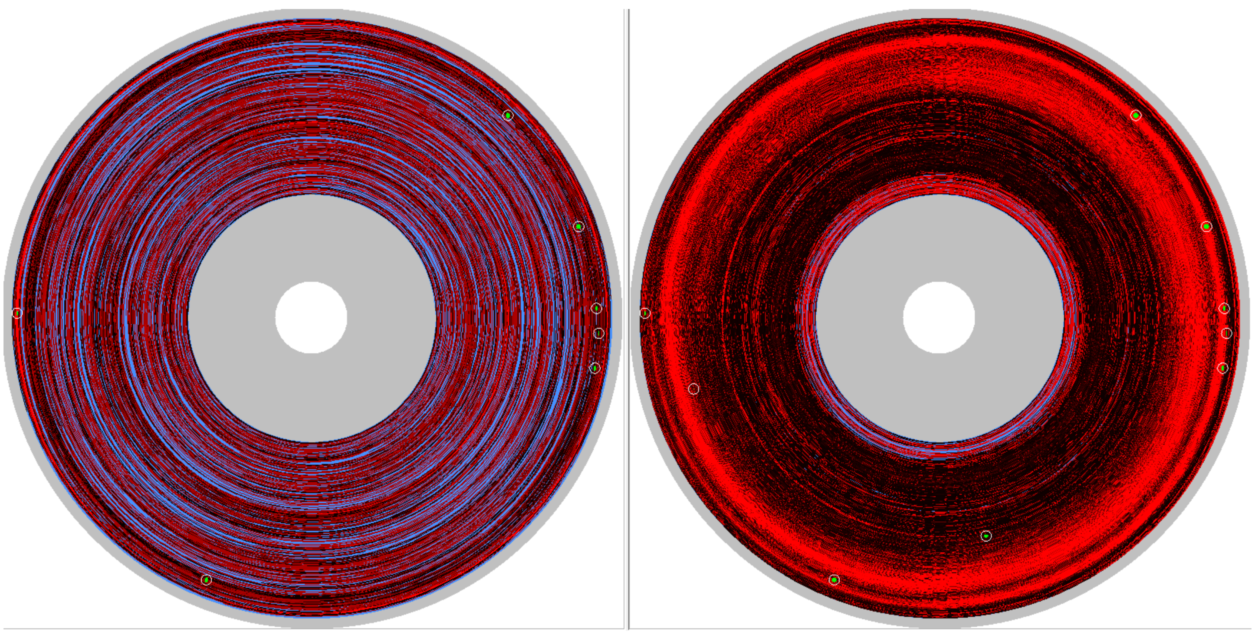

**Figure 4-17: MI1 PIE Comparison of 12 vs 24 Hours**

It is readily apparent that the PIE errors increased abnormally only after 24 hours of artificial aging. Using nearly the same rotation of defects as in Figure 4-14, the highest concentrations of errors visible on the disc view matched well with the black spot defects radially. This is displayed in Figure 4-18.

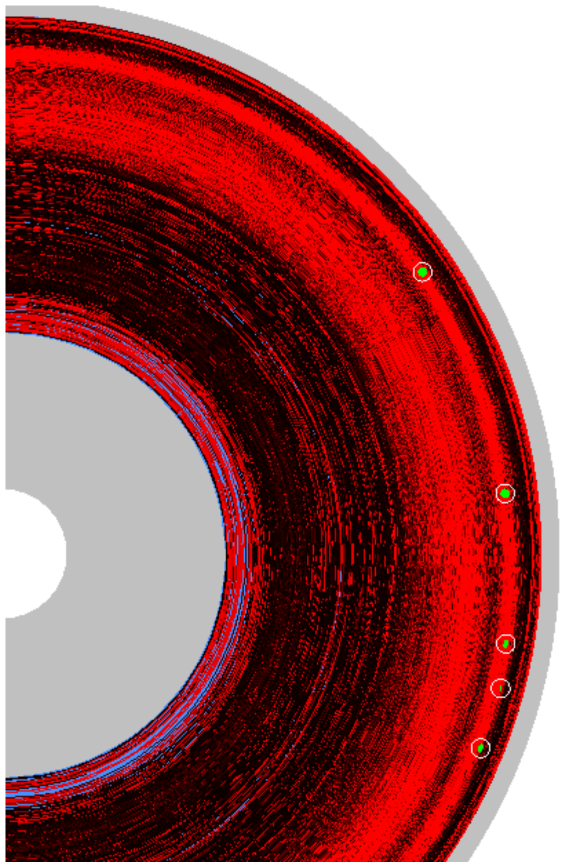

**Figure 4-18: MI1 PIE at 24 Hours Rotated to Match Radial Bands**

While no conclusive evidence was gathered to link digital errors to physical defects, too many coincidental similarities existed to rule out multiple, equally likely, matching positions.

### 4.5.2 MI2

The MI2 disc exhibited the same degradation observed with the MI1 disc but to a smaller extent. Namely, a black spot defect smaller than those of MI1 appeared at the 12 hour iteration. This defect, however, could not be seen in the digital camera image. Several other defects were observed, but were mainly superficial marks or contaminants. The disc view using the POF error type showed immediate results at 24 hours as only two ECC blocks appeared to contain any POF errors. These matched remarkably well with the black spot defect, as shown in Figure 4-19.

**Figure 4-19: MI2 POF at 24 Hours with Defect Rotated**

The comparison between the defect and the POF error block is shown magnified in Figure 4-20.

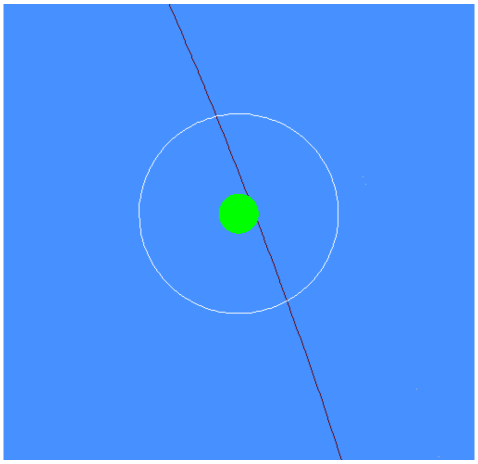

**Figure 4-20: MI2 POF at 24 Hours Magnified Comparison**

The offset between the centers of the error filled ECC block and defect is less than 0.15mm, which can be attributed to the standard error of the defect measurement process as radial measurements were made in only 0.5mm increments.

Just as the MI1 disc, this disc displayed little difference in PIE errors in the disc view until the final iteration of 24 hours. By utilizing the ECC block center graph at 12 hours, several localized centers were marked. One of these at 51.5mm and 73.5° lined up almost perfectly with the black spot defect, as shown in Figure 4-21. It is also clear from the image that the marked center resided in one of the highest concentrations of errors on the disc from the bright red color.

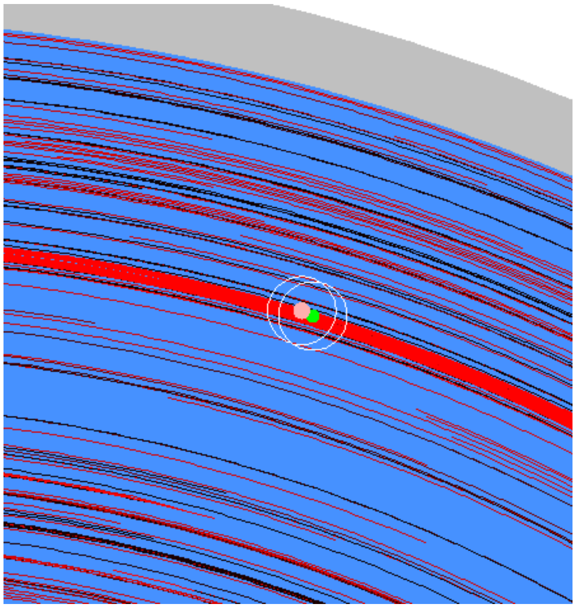

**Figure 4-21: MI2 PIE at 12 Hours with Marked ECC Block Error Center**

The same result with this defect and a marked center was obtained at 24 hours near the same angle, as shown in Figure 4-22. Here the defect is shown offset from the marked center as when it is rotated, it is completely covered by the mark. Hence they are at precisely the same radius and angle.

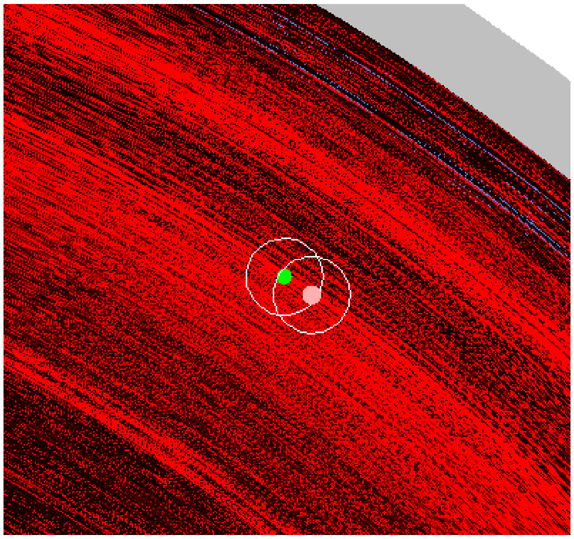

**Figure 4-22: MI2 POF at 24 Hours with Marked ECC Block Error Center**

The examples from this disc were able to demonstrate that physical defects can relate almost exactly to the digital errors. Furthermore, it showed that SectorDraw was able to present the data in a format that emphasized these similarities.

### 4.5.3 VB1

The VB1 disc was one of two that did not survive the three full iterations. After 24 hours of artificial aging, the Shuttleplex was unable to successfully analyze the disc and it was determined to have failed. Similar to the MI1 and MI2 discs, black spots appeared in the final iteration around the outer edge near 56.5mm. No direct comparisons were able to be found for the black spots as the error analysis did not exceed the 46mm radius. However, the partial analysis presented unique evidence that pointed to physical defects as the main culprit for the failure. It revealed that all observed defects resided outside the analyzable area as shown in Figure 4-23. This fact strongly suggests that the defects caused errors in the readback of the disc and actually caused it to be unsuccessfully analyzed.

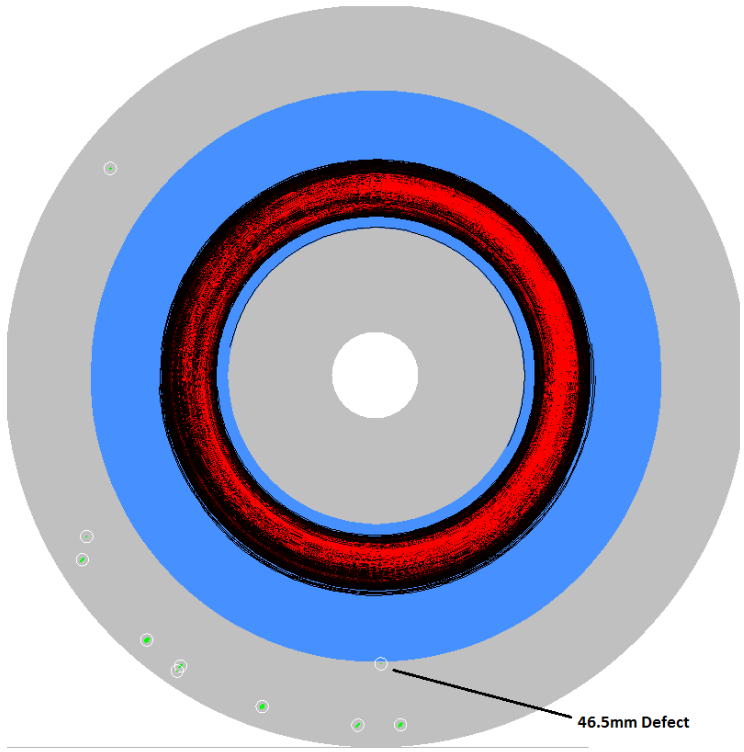


**Figure 4-23: VB1 POF at 24 Hours Partial Analysis**

It is interesting to note that the first defect radially at 46.5mm was not a superficial mark. It was deemed an injection flaw, a defect present even before data was written to the disc. The actual difference between the end of the analysis data and the defect was only 0.5mm, which could be attributed to standard error in measuring defect position. While the data gathered from the VB1 disc was not as plentiful as others, it established a definite relationship between the observed defects and the digital error analysis.

## 4.6 Analysis

It was stated in Chapter 1 that three questions had to be answered before the framework was fully constructed:

- How should physical defects be evaluated and characterized?
- What is the relationship between observed physical defects and digital errors?
- How do physical defects develop over time in artificially aged media?

In the end, the answers to these questions were found as the framework was developed through a process of trial and error. Certain aspects of the framework were established in order to answer them. It was found that physical defects should be evaluated and characterized based on a manual process of conducting visual inspection, microscope examination, and finally measurements. The relationship between physical defects and digital errors was strongly established with the initial SectorDraw validation. This experiment proved a successful in providing a hard link between the physical and the digital worlds. Finally, physical defects appeared to develop over time in artificially aged media linearly, although further study would be required to determine the true behavior. As the discs were aged, defects developed and were observed after each iteration of treatment.

The purpose of the research conducted was to develop and validate a framework for studying these properties. While no formal conclusions could be reached from the examples given in this chapter, the framework itself was proven to be able to study the relationship between physical defects and digital errors. In short, the framework was successfully constructed and validated. However, certain aspects of the framework were proven to be more useful than others. In fact, some even were found to be almost useless in their application. The Dr. Schwab image served as a fitting example of an aspect that was assumed initially to present informative data as the condition of the disc, but was shown to have no application in the end. The digital camera image, while demonstrated to be very powerful during the initial SectorDraw validation where larger marks or defects were observed, was determined to have difficulties showing the smaller observed defects during the validation study. Certain error types were also shown to provide no unique data or present information which was difficult to utilize. Additionally, features were developed for SectorDraw which were found unnecessary currently. One example of this is the zooming and panning features. These were rarely if ever used in the analysis of the study.

On the other hand, certain aspects of the framework proved to be extremely useful and informative. The SectorDraw disc view was one of these. Surprisingly, the ECC block center graph, a feature that was developed as an experimental analysis tool, became one of the most valuable for studying digital errors. Using these two views with the PIE, POF, and sometimes PIE 8 error types was shown analytically to be the most effective manner in which to use the framework. This data was backed up by observations made during the course of the analysis.

# 5 CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Research Summary

The methods used to store data on DVD-R discs have been proven to work over the last 15 years. However, there has been a growing concern that these discs will be outlasted by the paper records they were meant to replace. The data on a DVD-R is stored as optical contrasts which have the potential to be misread and even damaged. This damage may occur either on the surface or internally to the disc, especially on the recording layer itself. There are multiplestudies in the literature attempting to determine the time period in which discs may fail and what the general signs of the degradation are, but almost all fail to determine the fundamental causes of DVD degradation. In particular, the exact connection between the physical state of the disc and its digital errors is undetermined. This study undertook to develop a framework to study and understand this relationship. This would then serve as the foundation for further research to potentially reduce these physical artifacts or their fundamental causes by addressing the root problems of disc degradation. Additionally, by applying the framework to both artificially and naturally aged discs, comparisons could be made to further establish the validity of artificial aging.

The developed framework was specifically intended to characterize physical defects and relate them to digital errors. In order to do this, three questions had to be addressed:

- How should physical defects be evaluated and characterized?
- What is the relationship between observed physical defects and digital errors?
- How do physical defects develop over time in artificially aged media?

The study also consisted of a small-scale experiment designed to validate the usefulness of the framework. It was not intended to catalogue all possible types of defects or even to understand their relationships with digital errors completely. For this reason, it was developed as a characterization and not a statistical study.

The literature served to paint the backdrop of the research, but was insufficient to answer the questions posed. DVDs in general and DVD-R specifications more specifically were explored fully to understand methods of storing data on these optical discs. Specifically, DVD-Rs use a well-documented process of encoding data for storage which includes scrambling, modification of the data to include error correction codes (ECC), interleaving, modulation, and addition of synchronization data (Standard ECMA-279: 80 mm (1,23 Gbytes per side) and 120 mm (3,95 Gbytes per side) DVD-Recordable Disk (DVD-R) 1998). The final result is then written to a disc by making dark marks with a laser in an organic dye overlaid on a metal reflective layer (Worthington 2006). When reading back the data, the phase or amplitude of the return signal is used to detect optical transitions. These are then quantized into a string of ones and zeros and decoded to form the original data stored on the disc. The nature of this process as a whole is very susceptible to noise (Finkelstein and Williams 1988). In addition, physical defects in or on the disc can also cause damage to the data or interfere with the reading process (Bergmans 1996) (Pohlmann 1992).

Although many specific studies in the literature focused on lifetime estimation of optical discs with which this study was not concerned, several mentioned or explored the causes of data degradation. These identified four root degradation causes in optical discs: dye degradation, corrosion, oxidation, and delamination (Lunt and Linford 2009) (Shahani, Manns and Youket n.d.). Manufacturing defects are also documented as preventing the correct reading of optical discs in some conditions (Pohlmann 1992). While these failure mechanisms are generally explored and accepted, their exact relationship to both specific physical defects and digital errors was not discovered in the literature.

The framework constructed during the course of this research was developed from a process of trial and error utilizing varying tools and software. These included an environmental chamber used for artificial aging, a Shuttleplex media analyzer for analyzing digital errors, an argus XE device commonly called Dr. Schwab for analyzing an optical disc’s condition, microscopes for studying physical marks, and a digital camera for recording images of discs. A major gap was identified in the assistance provided by the tools available: no tool could aggregate the different sources of information into a singular view for study. For this purpose, a software program called SectorDraw was developed as part of this study. This tool represented the digital error analysis for a given DVD error type in a graphical view which could be overlaid with additional data including results from all devices mentioned above. It also provided functionality to navigate to and select specific sections of the disc in a magnified view. In this manner, the data from research such as the validation study conducted here could be combined into sets of data for a particular disc. Finally, it was extended to generate a graph to help in locating the relative “center” of groups of errors in adjacent ECC blocks, called the ECC block center graph.

In order to prove the functionality and use of SectorDraw, an initial validation was conducted using artificial artifacts made with a permanent marker on a DVD-R filled to storage capacity. Data was collected using the Shuttleplex analyzer and a digital camera for the disc before making any marks and again after making two and four marks. This data was aggregated using SectorDraw to study the relationship between the marks, or artificial physical defects, and digital errors. The digital camera image was also overlaid on the digital error representation to further understand the connection.

For the framework validation study, several DVD-Rs from various brands were selected to represent archival quality discs. After some initial observations, these discs were each filled with data and then subjected to a series of tests administered in an iterative manner. First, each disc was studied by manual visual observations with and without microscopes. An image was taken with a digital camera, and analysis with both the Dr. Schwab tool and the Shuttleplex was completed. After all observations were recorded, the discs were collectively subjected to elevated light, temperature, and humidity in an environmental chamber for 12 hours. This process was then repeated until a majority of the discs obtained error values higher than the documented maximum for a DVD-R. The results were then collected and organized into a set of data for each disc to utilize in SectorDraw.

The results of the initial validation of SectorDraw were very telling for just how powerful the tool was in understanding the connections between the artificial physical defects and digital errors. The program was able to create a visual representation of error locations and densities on the disc. The digital camera image was able to be overlaid on this view to see the physical marks. From this, a direct comparison was able to be established between each mark made on the disc and a group of errors obtained from the Shuttleplex analysis. In short, the SectorDraw proved an invaluable asset to ascertain relationships between physical marks and digital errors.

In order to analyze the results of the framework validation study, two measurements with scales and criteria were created. The first dealt with the different error types available to be rendered within SectorDraw. The utility of each was quantified using specific criteria and comparison grids were constructed. This showed that the PIE, POF, and PIE 8 error types provided the most useful information, in that order. Using these results, the second measurement utilizing quantifications on specific criteria was conducted on each aspect of the framework to derive the most useful sections and tools. After comparing the results, it was determined that the features presented by SectorDraw was the most useful aspect of the framework overall. The manually observed defects, ECC block center graphs constructed by SectorDraw, and digital error disc view presented by the software were concluded as the next most useful aspects. From the data and experience gained over the course of the research, the digital camera images and Dr. Schwab results were determined to be of little use in the framework overall, although exceptions were present for the digital camera images.

The last step in the validation of the framework was to gather several examples utilizing the most useful aspects of the framework with the error types that provided the greatest amount of unique information. This was completed with three discs chosen from a composite rating from the previously gathered measurements. Each disc presented specific and significant examples of observed physical defects relating extremely well to digital errors. Although the study was not statistical in nature and therefore no conclusive evidence could be gathered to specifically state the relationship between physical defects and digital errors, the framework was proven to effectively enable the study of these comparisons. More importantly, it confirmed that a definite relationship exists. In short, the framework was successfully validated.

The final recommended process to utilize the framework consists of a shortened version of the above steps. First, the DVD-R media must be prepared by writing data to each disc. Iterations of disc analysis and treatment would then follow until the data gathered is considered sufficient. Each iteration would consist of analysis with the Shuttleplex, manually studying defects with the naked eye, eye loupes, and microscopes, taking an image with a digital camera, and finally aging all discs in an accelerated manner as recommended in Chapter 3. It must be noted, however, that the process and utility of manual defect observations and the digital camera image could be vastly improved by recommendations to follow.

In the course of this study, the three questions initially presented were answered. It was discovered that physical defects should be evaluated and characterized by using a process of visual inspection, microscope examination, and measurements. Although not all relationships between physical defects and digital errors were explored, the study established the fact that defects can directly cause bursts of digital errors. Lastly, it was found that defects developed over time after treatments of artificial aging. The developed and validated framework was established as viable for future research to study specific relationships between physical defects and digital errors.

## 5.2 Recommendations

The framework developed over the course of this study opens many possibilities concerning future research. A larger, statistical based study utilizing the framework is recommended to fully understand the fundamental physical causes of digital errors. It is believed that the validation study conducted herein was a first step towards this end.

Additionally, improvements are recommended to increase the efficiency of the framework. Many of these involve automating processes to remove tedious or unnecessary steps. A list of these improvements is as follows:

- Automation of the defect observations by microscope. An X-Y table could be integrated with the microscope and interfaced with the SectorDraw software to automatically search for and capture images of possible defects. These potential matches could then be searched manually for actual defects. This would save enormous amounts of time and effort.
- Automation of the ECC block center marking on the generated graph and on the disc view. An image-recognition algorithm could be used to automatically define the sizing and placement of markers to compare against physical defects.
- Automation of the cropping process of the digital camera images to match the borders of the disc. An image recognition algorithm could also be used in this case to crop images.
- Improvement to the quality of the digital camera images. This may involve the usage of a higher quality camera or use of more professional equipment to reduce glare on the disc.
- Development of an algorithm to automatically rotate observed defects to the closest match for digital errors in the disc view and account for measurement errors. An algorithm is partially completed, but needs further work before it is ready to use.
- Improvement of the speed of SectorDraw rendering. Time was often wasted waiting for SectorDraw to draw the next set of images or graph. This would likely occur by further developing the usage of buffered images in rendering.

- Completion of the development of configuration files of SectorDraw by including saving and loading transparency values, rotation values, current overlays, selected objects, and current image sets.
- Automation of the process of creating observed defect configuration files. This would likely occur with completion of automating the microscope observation process.

It is also recommended that the Dr. Schwab analysis be removed from the framework entirely as it did not provide any information that was useful for the analyses conducted.

# APPENDIX A. RATING RUBRICS

This appendix contains the rubrics used to rate error types and aspects of the framework for analysis. These are referenced in Section 4.4.

## A.1 Error Type Rubric

The following rubric was utilized in rating and ranking ECC error types.

| *Rating* | *1* | *3* | *5* |
|---|---|---|---|
| Disc View | No bands of errors are visible. Disc view is identitical to other error types. | Difficult to separate bands of errors from one another. Disc view is mostly distinct from other error types. | Presents distinct and easily discernable bands of relatively high values of errors. Disc view is distinctly different than other error types. |
| ECC Block Center Graph | Graph presents no localized concentrations. View is identical to other error types. | Concentrations are present on the graph but are too large to localize possible defects. View is mostly distinct from other error types. | Localized concentrations of errors present easily identifiable possible defects. View is distinctly different from other error types. |

| | | | |
|---|---|---|---|
| Comparisons to Defects | No correlation between defects and identified localized errors in disc view or ECC block center graph. Comparisons made are identitical to other error types. | A correlation exists between defects and identified localized errors in the disc view or ECC block center graph. Comparisons made are mostly distinct from other error types. | High correlation or possibility of correlation between defects and identified localized errors in the disc view or ECC block center graph. Comparisons made are distinctly different from other error types. |
| Data Over Time | Views remain static through different iterations. Views are identical to other error types. | Views change through iterations but provide less information or decrease in ability to detect localized errors, or views increase in the number of errors but very suddenly (i.e. high numbers of errors in the last iteration only). | Views steadily increase in the amount of errors with each iteration. The changes also make it easier to detect localized errors. |

### A.2 Framework Aspect Rubric

The following rubric was utilized in rating and ranking different aspects of the framework.

| *Rating* | *1* | *3* | *5* |
|---|---|---|---|
| Identifying Localized Errors | Aspect does not present localized areas where defects could potentially lie. | Aspect presents localized areas of potential defects, but only in a single iteration or not consistently. The localized areas do not correspond well to defects or other sources of data. | Aspect presents localized and specific areas of defects throughout most iterations. These localized areas correspond well to defects or other sources of data. |

| | | | |
|---|---|---|---|
| Physical to Digital Connection | Aspect does not establish a correlation between physical defects or marks and digital errors in any iteration. | Aspect establishes a correlation between physical defects or marks and digital errors. These correlations can only be observed in a single iteration. | Aspect establishes a strong correlation between physical defects or marks and digital errors. These correlations can be observed in most of the iterations. |
| Data Over Time | Aspect information remains static through different iterations. Aspect information is identical to another aspect's information. | Aspect information changes through iterations but decreases in utility, or its ability to relate digital errors to physical defects. Aspect information increases in utility only in the last iteration. | Aspect information steadily increases in utility, or its ability to relate digital errors to physical defects. |
| Ease of Use and Viewing | Aspect is complicated in use or slow in rendering and usage. Analysis cannot be made from aspect information without manual intervention. | Aspect is readily accessible but is slow in rendering or usage. Analysis can be made from aspect information with minimal manual intervention. | Aspect is quickly and readily accessible without effort. Analysis can be made from aspect information without manually intervention. |
| Ease of Gathering Information | Gathering data for this aspect takes long periods of time (greater than 1 hour) and effort. Tools related to the aspect are not readily accessible or automated, and large amounts of effort is required to extract useful data for analysis. | Gathering data for this aspect requires intermediate periods of time (1 hour or less). The process is partially automated and requires some effort to extract useful data for analysis. | Gathering data for this aspect requires little to no time (5 minutes or less). The process is fully automated and requires no additional effort to extract useful data for analysis. |

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