Imaging Methods Applied to Mechanical Sound Carrier Preservation and Access
Lawrence Berkeley National Lab
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- Founded in 1931 by E.O. Lawrence
- Oldest of US National Labs
- Operated by the University of California for the US DoE
- 4000 Staff, 800 Students, 2000 Guests
- 14 Research Divisions including
  - Physics, Nuclear Science
  - Materials, Chemical Science
  - Life Sciences, Physical Bioscience
  - Energy and Environment, Earth
  - Computing
- Major user facilities-
  - Advanced Light Source
  - Nat. Center for Electron Microscopy
  - Nat. Energy Research Super Computer Center
Collaboration and Support

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Introduction

• We are developing methods of optically recovering mechanical sound recordings \textit{without contact} to the medium

• Address concerns of the preservation, archival, and research communities:
  – Preservation: The reconstruction of delicate or damaged media
  – Access: Mass digitization of diverse media

• The approach evolved naturally out of methods of optical metrology, pattern recognition, and image processing at use in our lab.
Non-Contact Digital Imaging

- Create high resolution digital map of entire surface
- Computer plays record with a virtual stylus
- Protects samples from further damage
- Repair existing damage through “touch-up”
- Offload aspects of restoration to automated software

A “smart” copying machine for records
History

- 1859 Leon Scott invents Phonoautograph paper recorder
- 1877 Thomas Edison invents sound reproduction on tin foil Phonograph
- 1885 Bell and Tainter introduce wax cylinder
- 1887 Emile Berliner invents disc Gramophone
- 1925 Western Electric Orthophonic (electrical) system end of the “Acoustic Era”
- 1929 Edison production ends, lacquer transcription disc introduced
- 1947 Magnetic tape in production use, Ampex 200A
- 1948 33 1/3 rpm LP introduced
- 1958 Stereophonic LP on sale, uses 45/45 system
- 1963 Cassette magnetic tapes
- 1982 Compact Disc (CD) end of the “Analog Era”
- 2001 Apple IPOD
Diverse media

Shellac disc ("78"): main commercial media before vinyl (1950’s), scratches, wear, breakage

Wax and plastic cylinders: mold growth, wear, breakage

Lacquer, Al disc: instantaneous records pre-tape (~1948) exudation, flaking

Plastic belts: dictation, monitoring (1940’s-60’s), folds, cracks, wear

Metal stampers

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Mechanical Recording Principles

Cylinder: groove varies in depth (hill and dale)

Disc: groove moves from side to side

Ø2.1875

0.01 - 0.005 inch

groove spirals around cylinder, 100-200 tracks per inch

Vertical cut recording, surface varies locally.

~< 20 microns

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Debate during acoustic years between cylinder (constant surface speed) and disc (ease of manufacturing and storage) technologies.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>78 rpm, 10 inch</th>
<th>Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut</td>
<td>Lateral</td>
<td>Vertical</td>
</tr>
<tr>
<td>Area containing audio data</td>
<td>38600 mm²</td>
<td>16200 mm²</td>
</tr>
<tr>
<td>Total length of groove</td>
<td>152 meters</td>
<td>64-128 meters</td>
</tr>
<tr>
<td>Max groove amplitude (microns)</td>
<td>100 - 125</td>
<td>~10</td>
</tr>
<tr>
<td>Groove depth (microns)</td>
<td>80 fixed</td>
<td>+/- 10 varies</td>
</tr>
<tr>
<td>Groove displacement @noise level</td>
<td>1.6 - 0.16 microns</td>
<td>&lt; 1 microns</td>
</tr>
</tbody>
</table>

Information is encoded in sub-micron scale structures which are >100 meters long.
Micro-photograph of shellac disc: A two dimensional image “2D” can measure lateral grooves

Surface profile of a wax cylinder: A three dimensional image “3D” is required for vertical cut grooves
The Method

- Digitally image the surface
- Cover with sequential views or grid.
- Stitched together: surface map
- Process image to remove defects
- Analyze shape to model stylus motion.
- Sample at standard frequency
- Convert to digital sound format.
- Real time playback is not required
2D Imaging: Electronic Camera

- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface
- Coaxial illumination
Speed and Data

- 2D scans for lateral discs
- High frame/line rate electronic cameras
- High intensity light sources
  - Fast camera: ~10 min for 78 rpm disc
- Data
  - 50 Mb / 1 s of raw images
  - 1.5 Mb / 1 s processed
  - 88 Kb / 1 s audio (44/16)
Chromatic Aberration
3D Imaging: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.

Point by point scan
0.01 degree = 96 KHz

Up to 4000 pts/second
≈ 5 micron point size

Surface of an Edison cylinder
Speed and Data

Fundamental drivers are: probe rate, grid (time x profile)
Speed and Data

• 3D scans for vertical cylinders
  – Depends upon grid, probe rate, recording & surface characteristics
  – High sampling: 24-80 hours
  – Factors of 2-4 may be available soon

• 3D for deep groove lateral discs
  – Much slower probe rates are probably required

Key 3D issues are slope and depth
Analog waveform

Low-pass filter

$\frac{f_0}{2} < f_{\text{sample}}$

Commercial CD: 16 bits, 44.1 KHz

Archive spec: 24 bits, 96 KHz
Segmented image determines sampling

Natural segmentation by pixel size (2D), grid (3D) magnification, resolution

Easily time sample to 300 KHz

Amplitude sampling set by resolution
~0.3 microns / 250 microns max (2D)
~0.1 microns / 25 microns max (3D)
Not 16 bits!
Issue of Aliasing

• Sampling theorem
  1. Sample at $2f$ where $f$ is highest frequency of interest
  2. Apply low pass filter above $f$ to prevent aliased components appearing in data unless noise above $f$ can be neglected.

• In optical approach sampling is done by pixelization of image.
  1. High sampling frequency
  2. Use of pixel size to achieve effective low pass filtering?
Image Analysis

2D

Fits to data provide estimate of depth

3D

Groove geometry is unique and provides a powerful constraint on data

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What is the relationship between “groove” and sound?

Electro-magnetic case

- **induction**

Acoustic case

- Diaphragm is over-damped to provide flat response

Max. Slope = Max. Sound

Amplitude

Wavelength

Sound = Stylus Velocity

(“constant velocity condition”)

\[ A_p = \frac{v_p}{2\pi f} \]
Acoustic Case

- Horn extends response (of small diaphragm) to lower frequencies
- Plane waves: pressure and velocity are proportional and in-phase
- Horn supports plane waves: true above a cut-off frequency for sufficiently large horn, depends also upon profile
- Diaphragm is a driven harmonic oscillator
- Want “flat” frequency response: requires overdamping
- Diaphragm velocity follows driving force (fails at high frequency where mass dominates (~5KHz))
- “Constant velocity” condition applies approximately but no deliberate equalization is possible.
- Response
  - Typical ~1 decade
  - best case 100 Hz-5KHz
Stylus Velocity and Filtering

- **Finite Difference Method “FD”**
  - Calculate slope at each point
  - Point set imposes high frequency rolloff
  - Slope (at n) = A(n-2) – A(n+2) / interval

- **Local Fit Method “Pnn”**
  - Fit polynomial to sets of points
  - Complex high frequency effect

- **Frequency method (Fourier FOU)**
  - Use all information in data up to maximum frequency
  - Can apply explicit filters
Numerical Differentiation and Filtering

\[
\frac{d}{d(nT)} A_F(nT) = \frac{d}{d(nT)} F_D^{-1}[C(k)] = \frac{1}{N} \sum_{k=0}^{N-1} \frac{d}{d(nT)} M(k)C(k)e^{-ik\Omega_nT}
\]

\[
= \frac{1}{N} \sum_{k=0}^{N-1} (-ik\Omega)M(k)C(k)e^{-ik\Omega_nT}
\]

The filtering factor:

\[
M = \begin{cases} 
0 & \text{for } f < 20\,\text{Hz} \\
1 & \text{for } f \in [20\,\text{Hz}, 4.8\,\text{KHz}] \\
1.0 - \left(\frac{f - 4.8}{0.4}\right) & \text{for } f \in [4.8\,\text{KHz}, 5.2\,\text{KHz}] \\
0 & \text{for } f > 5.2\,\text{KHz}
\end{cases}
\] (23)

Perform the differentiation and filtering in a single processing step by:

- Doing FFT transform
- Applying \((-i \, k \, \Omega) \, M(\kappa)\) factor
- Doing reverse FFT transform
- Or simpler point by point methods
Comparison

- Data intensive
- Scanning speed (particularly 3D)
- Is fidelity sufficient?
- Powerful restoration methods for audio already available

♫ Non-contact
♫ Robust – wax, metal, shellac, acetates…
♫ Effects of damage and debris reduced by image processing
♫ Re-assemble broken media
♫ Resolve noise in the “spatial domain” where it originates.
♫ Use of groove geometry.
♫ Effects of skips are reduced.
♫ Distortions (wow, flutter, tracking errors, etc) absent or resolved as geometrical corrections
♫ Operator intervention during transcription is reduced, mass digitization.
ΔR distribution

Width across groove bottom

Measure slope at each point (stylus velocity)

Align
Average
Filter using ΔR<cut

TIME

Measurement spacing along time axis ~ 66 KHz

ΔR

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Sound Comparison

“Goodnight Irene” by H. Ledbetter (Leadbelly) and J.Lomax, performed by The Weavers with Gordon Jenkins and His Orchestra ~1950

- optical readout.
- mechanical (stylus)
- CD re-mastered tape.

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Projects Underway

• Concept was tested 2002-2003 leading to interest and support from the Library of Congress and others.

• IRENE: a fast 2D optical scanner for disc records
  – Digital access to the most common media + special formats

• 3D scans on “Edison” cylinders
  – Preservation and restoration of early and damaged recordings
  – Proposal to develop a 3D scanner for the Library of Congress

• 3D scans on plastic dictation belts
  – Feasibility study for preservation transfers of damaged media
I.R.E.N.E.
Image, Reconstruct, Erase Noise, Etc

- ~1 year development and construction
- Experimental “production” machine and test-bed for future development
- Emphasize throughput and diversity (access), scan time ~10-15 minutes
- Provide statistical measures of media condition
- Currently under evaluation
Line Scanning: disc is in motion

- 6000 pixels@15 K lines/s
- 7.6 x 10^5 lines/outer ring
  - 390 KHz max sampling
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.
ΔR distribution

Width across groove bottom

Measure slope at each point (stylus velocity)

Average Filter using ΔR<cut
Motion control

Camera+optics

CPU

Auto-focus sensor

Turntable+stages

Light source

Motion control

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Control and Analysis Codes
Eccentricity control

Label camera

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Groove Images

Lacquer disc

Shellac with moderate wear

Poor quality shellac, acoustic recording

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Status

• Hardware configured and scanning
  – 15 minutes for a 3 minute disc but >50% is overhead
• Main control, logging, and analysis code runs
• Main issues have been illumination and field of view, uniformity
• Can process most scans and extract sound
  – Significant study of parameters still in process
  – Logging: focus, illumination, magnification, sampling,…
  – Analysis: image processing, defect recognition, interpolation, filtering, differentiation, models,…
  – All can effect sound quality, noise, frequency response in a variety of ways.
Testing and Validation Phase

• 9-12 months in duration in the LC Recording Lab
• Led by Peter Alyea
• Machine to be tested on a significant sample of media
  – Quantitative comparisons with test (& other) records
  – Variety of media types and condition
  – Listening tests
  – Flat and historical EQ’s
  – Study scan parameters and analysis/reconstruction options
• Results to be documented and disseminated
• Possibility of a follow-on stage
  – Upgrades to software and/or hardware
  – Expanded media study
Media Condition Survey on LC Samples

- **good**: 65%
- **poor**: 10%
- **fair**: 25%

- **good lacquer**
- **exudated lacquer**

- Multiple edges
- Rough groove bottom

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Test Scan Examples

• A variety of media types and condition
• These are early test scans to validate that the process runs from start-to-finish
• Should not be viewed as final results. Those will follow the validation study and will be formally presented to the community and documented as agreed.
The Star Spangled Banner: Kate Smith

78 rpm shellac disc with moderate wear,
RIAA curve applied

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Goodnight Irene: Weavers 1950

Noise spectra

stylus

IRENE

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Studio Test 1947

Mutt Carey and his New Yorkers: Shim-Me-Sha-Wabble

Lacquer disc, RIAA EQ

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Acoustic Recordings, Worn

Dirty and worn
When You and I Were Young, Maggie
Composer: Johnson and Butterfield
Performed by Charles Harrison
Victor 17474-B

Stylus version
IRENE test scan

Poor image quality
In the Evening by the Moonlight
Performed by Columbia Stellar Quartette, Columbia A2683, 1918

Stylus version
IRENE test scan

Classified POOR in initial media survey
Memovox Disc

• Developed fixtures to temporarily flatten these
• Image features are less distinct than on shellac and lacquer discs
• Analysis still basic…
Interesting Lacquer Discs

78 rpm lacquer on glass
Label: Howard Hughes, Collier Award 1939

78 rpm acetate, Theos Bernard, interview, 1929
Cylinder Scans

- Cylinder History
  - 1877 Aluminum foil
  - 1885 Soft wax for original recordings and dictation
  - 1902 Hard wax molded, commercial
  - 1908 Cellulose molded, commercial “Amberols”
Sample at 96KHz to minimize effect of aliasing

Sequential axial scans

Subtract valleys from ridges to correct for overall shape

(Ridges provide (approx), geometrical reference)

Overall cylinder shape due to off-center, deformation, heard as low freq rumble

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Sound Comparison

- The Holy City, composed by Stephen Adams,
  The Edison and Skedden Mixed Quartet, Amberol 1601

- Stylus
- Optical
- Optical + filter + EQ
Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.
Damaged or Delicate Cylinders

• Optical restoration of commercial cylinders yields satisfactory results

• Historical value of recorded wax cylinders is greater
  – Earlier recordings
  – Field work
  – Dictation

• Fungus growth and other surface issues can seriously degrade these

• A research priority for the Library of Congress
Surface Damage = Sound Degradation
Ethnographic Recordings
Ishi, regarded as the last survivor of the Yahi tribe of No. California was recorded extensively by UC Berkeley Anthropologist Alfred Kroeber (circa 1915). This collection is held at the UCB Phoebe Hearst Museum.

Sam Batwai, Alfred L. Kroeber, and Ishi

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Ishi at Deer Creek
London Wax Cylinders

Jack and Charmian London

JL’s Dictaphone machines from the JL State Park

1st cylinder from JL house with mold growth visible

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1st Cylinder on 3D scanner
..soon after the affair, very tragically between England and America…
…the Lusitania…
I wish I had time to go and read your letters…..that it opens up… but I simply cannot….After the war is over I am intent upon going to England. And then making sure that we shall get together (period)

Voice of Charmian London 1915?
Dictation Belt Scanning

• Plastic dictation belts are historical documents
  – LBJ, JFK presidential phone conversations
  – Dallas PD recording of open mic 11/22/63 (NARA)

• Some belts are worn and cracked
  – NARA proposed a high resolution optical scan as a way to make a digital preservation copy and enable access.

• Scanning tests and analyses have been performed on recorded test belts and other samples.

• Recorded at 42 rpm: long scan times
Display of Tone Test Belt

Note complex groove profile
• Considerable non-linearity of the system.
• Bears on validation of process
• Bears on analytical applications
Optical Scanning: A general tool to preserve and create access to recorded sound history

Wax cylinder  Shellac disc  Plastic dictation belt

Web site URL: www-cdf.lbl.gov/~av


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