Imaging the Voices of the Past: Using Optics to Restore Sound Recordings
Collaboration and Support

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Outline

• Major historical collections of sound recordings exist which are degraded, damaged or considered at risk.
• Archives seek new technologies which can stabilize, preserve, and create access to these collections.
• We study methods inspired by optical metrology, image processing, and statistical data analysis, to recover sound recordings.
• A good illustration of how the approach of the physical sciences can benefit other fields of study.
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*
The Problems

- Extensive historical sound collections exist worldwide
  - At risk
  - Diverse materials
  - National Recording Preservation Act of 2000 "A bill to…maintain and preserve sound recordings and collections of sound recordings that are culturally, historically, or aesthetically significant…, " (Public Law 106-474; H.R.4846).

- Move towards large scale digitization of collections
  - Requires automated technologies
Issues for Archives

• **Preservation:** safeguard artifacts to satisfy any conceivable future need.
  – Prioritized process
  – Do no harm
  – Highest quality

• **Access:** put entire collections into digital form to provide broad access to the public.
  – Mass processing required
  – Diverse media and condition
  – Moderate quality
Diverse media and content

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
Mechanical Recording Principles

Cylinder: groove varies in depth (Vertical Cut)

Disc: groove moves from side to side (Lateral Cut)

Audio is encoded in micron scale features which are >100 meters long
Debate during acoustic years between cylinder (constant surface speed) and disc (ease of manufacturing and storage) technologies.
<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
Archives and collections now transfer recordings to more stable and accessible formats using modern stylus players and conservation protocols. Requires contact to the media and audio professionals.

We study the use of new, optical measuring and image processing methods to create a digital representation of the complete record surface, on the computer, and then “play” it with a virtual needle. This is a very general approach and no contact to the record is required.
Non-Contact Digital Imaging

• Preservation
  – Protects samples from further damage
  – Repair existing damage and debris through digital “touch-up”
  – Re-assemble broken samples
• Access
  – Offload many aspects of transfer to automated software
  – Handle diverse formats

A “smart” copying machine for records

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
- High speed cameras allow near “real-time” imaging

Coaxial illumination
3D Imaging: Chromatic Aberration
3D Imaging: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.

Point by point scan
0.01 degree = 96 KHz

Surface of an Edison cylinder

To cover the entire surface of a record requires many hours of scan time, depends upon grid size used.

Up to 4000 pts/second
Analog waveform

Low-pass filter

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

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 but intrinsically linear
Image Analysis (2D case)
What is the relationship between “groove” and sound?

Electro-magnetic case

Acoustic case

Diaphragm is over-damped to provide flat response

Sound = Stylus Velocity

(“constant velocity condition”)

Max. Slope = Max. Sound

\[
A_p = \frac{v_p}{2\pi f}
\]
Stylus Velocity and Filtering

- Measured groove profile must be differentiated
- Variety of numerical procedures
  - Implicit and explicit filtering effects
  - Stylus response modeling
  - Equalization
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.
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)
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

Average Filter using ΔR<cut

Measure slope at each point (stylus velocity)

Time

Pixels = 104 KHz

18-October-2006 CITRIS: C.Haber
The Star Spangled Banner: Kate Smith

78 rpm shellac disc with moderate wear, RIAA curve applied

18-October-2006

CITRIS: C.Haber

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Goodnight Irene: Weavers 1950

Noise spectra

record

IRENE
Studio Test 1947

Mutt Carey and his NYrs: Shim-Me-Sha-Wabble

Lacquer disc, RIAA EQ
Cylinders

- 1877 Aluminum foil
- 1885 Soft wax
  - Field recordings
  - Dictation
  - Commercial production
- 1902 Hard molded wax
- 1908 Molded cellulose
  - “Amberols”
3D Scan of Commercial “Edison” Cylinders

- Cylinder
- Rotating stage
- Translating stage
- 3D optical probe

Measured data

Reconstruction of groove profile in highlighted region

CITRIS: C. Haber
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

18-October-2006

CITRIS: C.Haber
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

- Fungus growth on wax cylinders destroys the surface
- Recrystallization alters surface texture
- Impacts unique samples – early recordings, field work, dictation

A research priority for the Library of Congress and a focus of our on-going effort
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
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

18-October-2006 CITRIS: C.Haber

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)
- Dallas PD belt is 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 underway on test belts
Optical Scanning: A general tool to preserve and create access to recorded sound history

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