New Imaging Methods Applied to Recorded Sound Preservation and Access

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Collaboration and Support

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America’s Collections

- US museums, libraries, and other institutions collectively hold 4.8 Billion items
- 46.4 million sound recordings
  - 14% are in need of preservation (6.5 million)
  - But 42% are in unknown condition (19.5 million)
  - And there is also the rest of the world
- Archivists want to reformat all pre-digital media since playback systems are not maintained

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<th>Fig. 4.1 U.S. Institutions Have Taken Responsibility to Preserve 4.8 Billion Collections Items</th>
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<td>Archaeological Collections, cataloged in cubic feet</td>
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Heritage Health Index 2005
What does the archive contain?

• Field recordings of linguistic, cultural, and anthropological materials…
• Primary recordings of key artists
• Field recordings of sources which underlie much of modern music, American and European folk traditions…
• Speeches & spoken words of historical figures, Edison, Churchill, Roosevelt…
• Early radio broadcasts (lacquers)…
• Live performances, events,….
• Early technical tests and experiments…
• Public and private dictation and monitoring records, intelligence, Presidential sources,…
• Commercial record releases…
Digitization

• Robotic scanning of texts and optical character recognition (OCR) are now in wide use at major libraries, Google…

• Unlike texts, digitization of historical sound recordings is often an invasive process-by definition
• At Berkeley we are developing methods of optically recovering mechanical sound recordings **without contact** to the medium – **like text scanning**

• Address concerns of the preservation, archival, and research communities:
  – Preservation: Restore or stabilize 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 in use for physics research.
History

- 1859 Leon Scott: *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*
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.
Sound Carrier Degradation

- Fungus
- Wax bloom
- Oxidation
- Exudation
- Breakage
- Dirt
- Flaking
- Warpage

11-April-2007

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Archives and collections now transfer recordings to more stable and accessible formats using modern stylus players, digitizers, and best conservation practices. Requires contact to the media and skilled 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
2D vs 3D Imaging of Discs

Measure the groove with 2-4 points/slice

Measure the groove with ~30 points/slice
Analog waveform

Low-pass filter \( f_0 < \frac{f_{\text{sample}}}{2} \)

Vin \( \rightarrow \frac{R}{C} \rightarrow \) Vout

ADC

Clock

Commercial CD: 16 bits, 44.1 KHz
Archive spec: 24 bits, 96 KHz

Time

Amplitude

Pixel: 100-400 KHz

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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
- Store results as standard digital sound files (.wav) and high resolution digital images
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: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.

Point by point scan
New Probe Technology

Measures 1 point at 1000 – 2000 per second

Measures 180 point simultaneously on 10 micron grid at up to 1800 per second
Speed and Data

• Point by point measurement
• Exposure time per point
• Grid along time direction (red) = digital sampling
  • 0.02 degree = 18,000 samples = 48 KHz
• Grid along axis direction (blue) = points per profile
  • Typically 5 – 10 microns
• 1 probe: ~ 80 hours for 2-4 minutes of audio
• 180 probes: ~ 20 minutes (new multi-fiber probes)
Image Analysis (2D case)

Feature extraction and measurement

Measured width of features provide a natural noise detection and removal tool.

3D images are analyzed in an analogous fashion
What is the relationship between “groove” and sound?

Electro-magnetic case

induction

Acoustic case

Diaphragm is over-damped to provide flat response

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

![Graph showing phase angle vs. frequency](image)

**Phase Angle (f0=5000 Hz)**

- Critical damping
- 20x overdamped
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
Comparison

- Data intensive
- Cost
- Scanning speed
- 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 and geometry
♫ Re-assemble broken media
♫ Resolve noise in the “spatial domain” where it originates.
♫ Effects of skips are reduced or eliminated.
♫ Distortions (wow, tracking errors, etc) absent or geometrical corrections.
♫ Operator intervention during transcription is reduced, mass digitization.
♫ Produce standard audio output data format (.wav)
♫ Can archive images for future re-analysis with new algorithms.
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
  - Installed at the Library of Congress 8/2006
- 3D scans on “Edison” cylinders and other media
  - Preservation and restoration of early and damaged recordings
  - R&D with the Library of Congress and special projects
- 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
- Currently under evaluation
Line scan

Width across groove bottom

Time

Pixels = 104 KHz

Measure slope at each point (stylus velocity)

Average Filter using width cut
Test Discs

Pristine new acetate disc scanned by IRENE
“Johnny”: Les Paul and Mary Ford
1953 recording, shellac 78 rpm disc is worn and scratched, distorted

Stylus version has a clear skip due to scratch

IRENE
Broken Record

Gilbert and Sullivan “Iolanthe” 1930 Victor 9708
Spoken Word Transcription Discs

78 rpm 16” acetate, ABC
“Greatest Story Ever Told”
#168, 1951

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

78 rpm acetate
Theos Bernard, interview,
1929
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
What Have We Learned So Far?

• Hardware Performance
  – Illumination
  – Focus methods

• Fidelity and Noise
  – Frequency response
  – Differentiation
  – Use of empirical EQ?
  – Broadband noise levels
    • What is fundamental?
    • Vary from disc to disc
    • Sensitive to focus
    • Insensitive to feature detection, illumination, sampling rate
    • Multiple feature detection
3D Media

- Wax cylinders
  - Damaged
  - Mold
- Edison commercial cylinders
- Diamond Discs
- Tin Foil
- Dictation belts
- Discs which image poorly in 2D
Sequential axial scans

Sample at 96KHz to minimize effect of aliasing

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

\[ \frac{d}{dt} \]
Sound Comparison

• The Holy City, composed by Stephen Adams,
The Edison and Skedden Mixed Quartet, Amberol 1601
Commercial cellulose release

• Stylus
• Optical
• Optical + filter + EQ
Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.
Surface Damage = Sound Degradation

- Fungus growth on wax cylinders destroys the surface
- Recrystallization alters surface texture
- Impacts unique samples – early recordings, field work, dictation
UC Berkeley Phoebe Hearst Museum holds an extensive collection of wax cylinders recorded by Anthropologist Alfred Kroeber and others. This sample is from the set recorded of Ishi (circa 1911-14).
Plastic Dictation Belts

- These were used for dictation, telephone and radio monitoring 1940’s-1970’s
  - US Presidential history
- Groove is embossed, lateral modulation, shallow
- Not meant as an archival medium, low fidelity, wide range
Forensic Applications

Dictabelt recorded by Dallas PD from a microphone at an unknown location

National Archives proposed a high resolution optical scan to make a digital preservation copy and enable access.
Dictabelt Scanning

150 μm

~ 4 μm
Study of test tone dictation belts

- Considerable non-linearity
- Bears on validation of process
- Bears on analytical applications
Prospects

• Disc scanning (2D, IRENE) is under evaluation at the Library of Congress now.

• Cylinder (3D) scanning is an R&D effort at present.
  – A number of proposals to develop a 3D scanner
  – Collaboration with UCB Linguistics and Hearst Museum to assess impact on Native American fieldwork recordings
  – Important implications for:
    • Early recording history
    • Fieldwork collections
    • Ultimate fidelity transfers from discs
    • Damaged media, dictation belts
Optical Scanning: Technology Roadmap

Basic 2D concept demonstration
40 min / 1 sec

2D disc R&D
4 sec / 1 sec

3D cylinder R&D
20 hr / 1 min

IRENE System eval
2006-2007

Production mode discs
2008?

3D System
10 min / 1 min

2007-2008 ?

Pilot study

2002

2003-2004

11-April-2007

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Optical Scanning: A general tool to preserve and create access to recorded sound history


Web site URL: http://irene.lbl.gov/
Line Scanning: disc is in motion

- 4000 pixels@~10^4 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!!!
Education and Outreach

• Example of methods from the physical sciences applied to other fields of research, culture, and public service

• Interesting and novel research experience for science and engineering and students
  – 7 undergraduates from EE, Comp Sci, and Physics

• Public presentations
  – ~50 seminars, radio, TV, newspapers, magazines, blogs,
    >200 Google hits, hundreds of email inquiries.

• Research opportunities for students from groups under-represented in science and engineering
Silver Threads Among the Gold: Elsie Baker 1913 Victor 17474-A
Early, acoustically recorded, shellac disc
Goodnight Irene: Weavers 1950
late model electrically recorded shellac disc
Studio Test 1947 Cellulose Acetate

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

Lacquer disc, RIAA EQ
Early Native American Fieldwork Collections
(partial list)

- **Library of Congress ~8500 cylinders**
  - Omaha Indian Music: collected by Alice Fletcher and Francis La Flesche ~1897—99
  - Francis Densmore
  - Helen Roberts
  - John P. Harrington
- **National Anthropological Archives**
- **Indiana Univ. Archives of Traditional Music, ~6000 cylinders**
  - Collection spans 1893—1938
- **UC Berkeley Phoebe Hearst Museum ~3000 recordings**
  - recordings by A.Kroeber and others
  - Linguistics collections
- **University of Washington Libraries**
  - Pacific Northwest Native American Materials in the Melville Jacobs Collection (and others)
Jack 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

1st Cylinder on 3D scanner
Audio Extraction

..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?
Display of Tone Test Belt

Note complex groove profile
Pilot Study

• Wax cylinders from fieldwork collections are a good example of 3D media
  – Collaborate with UC Berkeley, Phoebe Hearst Museum and Dept. of Linguistics: California Indian recordings

• Scan a range of samples to:
  – Bracket the performance of the process
  – Assess the realistic throughput for a larger project

• Practicalities
  – Software and hardware development to enable efficient data taking and analysis.
  – Incorporate new, faster probe.
3D Imaging: Chromatic Aberration