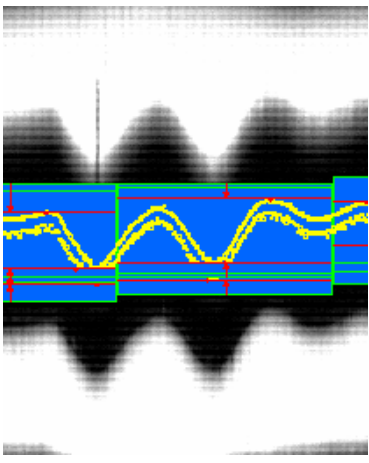
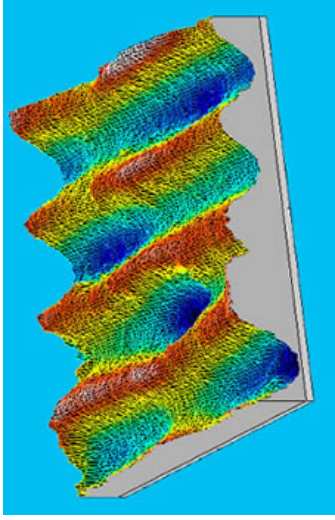




Using Optical Metrology to Restore Sound Recordings



Collaboration and Support

[Lawrence Berkeley National Lab](#): [Vitaliy Fadeyev](#), Earl Cornell, Bob, Nordmeyer, Jian Jin,

UC students

[University of Southampton, U.K](#)

[EIF Fribourg](#): N.Lutz, M.Yerly

M.Golden

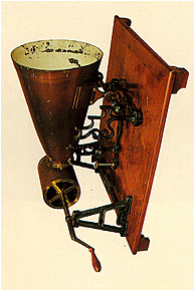
[Library of Congress](#): Peter Alyea, Larry Appelbaum, Dianne van der Reyden, Elmer Eusman

[Pepperdine Univ.:](#) Mark Roosa

[UCSB](#): Sam Brylawski

Financial Support from the Library of Congress, National Endowment for the Humanities, The Mellon Foundation, National Archives

Corporate equipment donations, discounts, loan, and services from Aerotech, Archeophone, JH-Technology, Keyence, Microphotonics, National Instruments, Navitar, Newport, STIL, Uniforce, Veeco, Vidipax, Visicon



Discos fonográficos Pathe
Caras y Caretas (17/1908)



- 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*

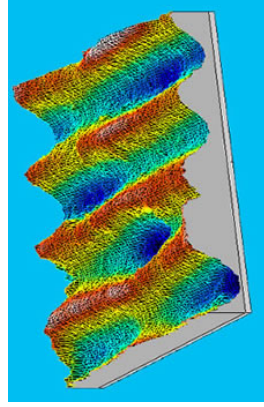
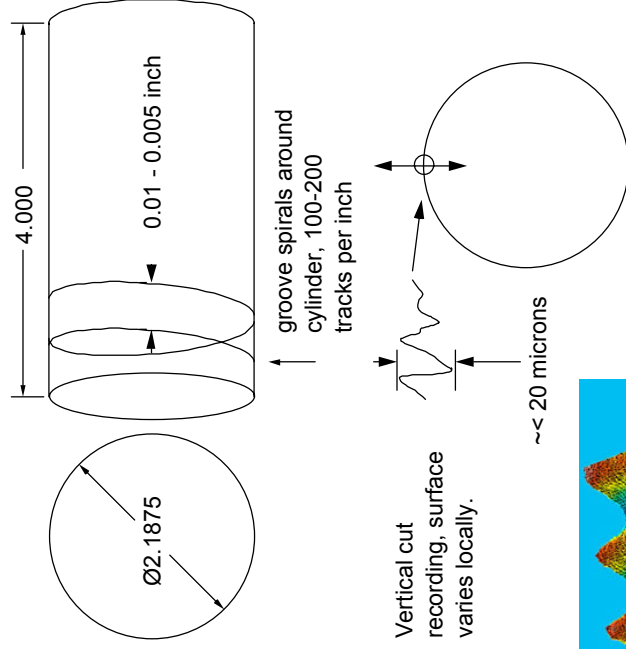
1, 2006

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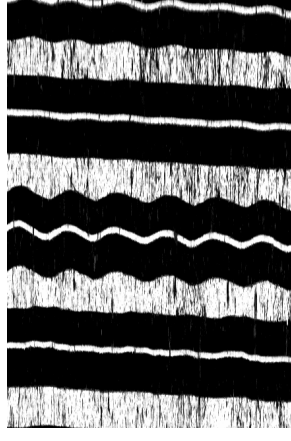
Mechanical Recording Principles



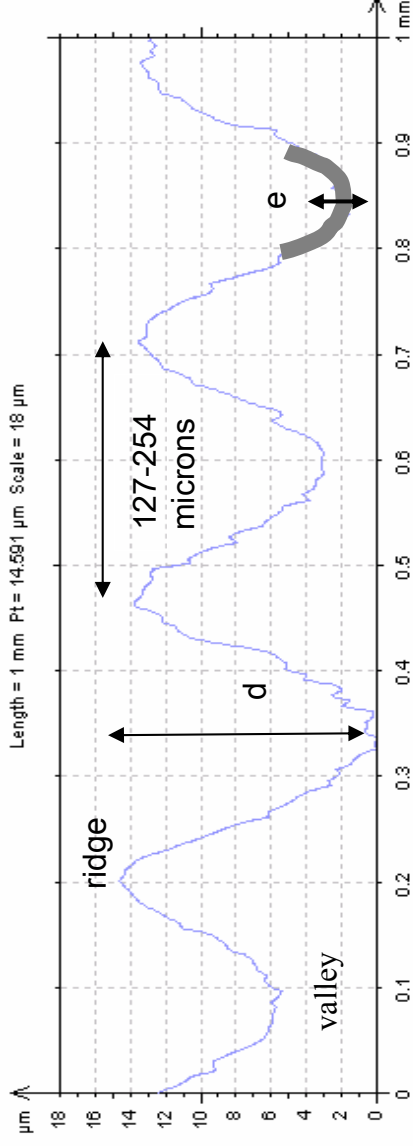
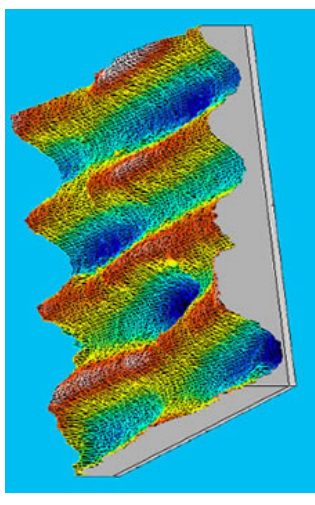
Cylinder: groove
varies in depth
(hill and dale)



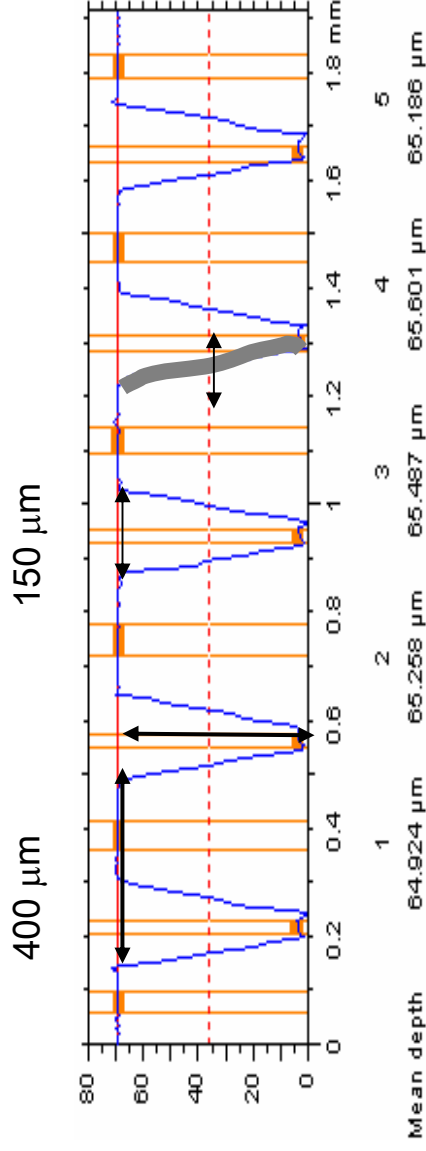
Disc: groove moves from
side to side



Cylinder surface



Disc surface



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

Parameter	78 rpm, 10 inch	Cylinder
Cut	Lateral	Vertical
Area containing audio data	38600 mm ²	16200 mm ²
Total length of groove	152 meters	64-128 meters
Max groove amplitude (microns)	100 - 125	~10
Groove depth (microns)	80 fixed	+/- 10 varies
Groove displacement @noise level	1.6 - 0.16 microns	< 1 microns

Information is encoded in sub-micron scale structures which are >100 meters long

The Problems

- Extensive historical sound collections exist worldwide

- Damaged
- Delicate
- Decaying
- Diverse materials



- Move towards large scale digitization of collections
 - **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).

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

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



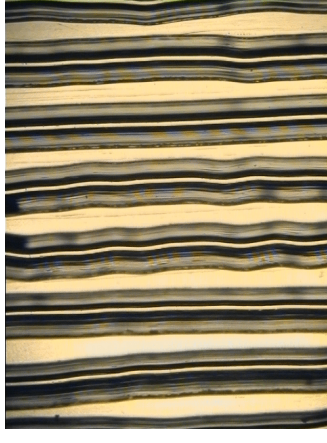
Lacquer, Al disc: instantaneous records pre-tape (~1948) exudation, flaking

May 31, 2006

Wax and plastic cylinders: mold growth, wear, breakage



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



Metal stampers

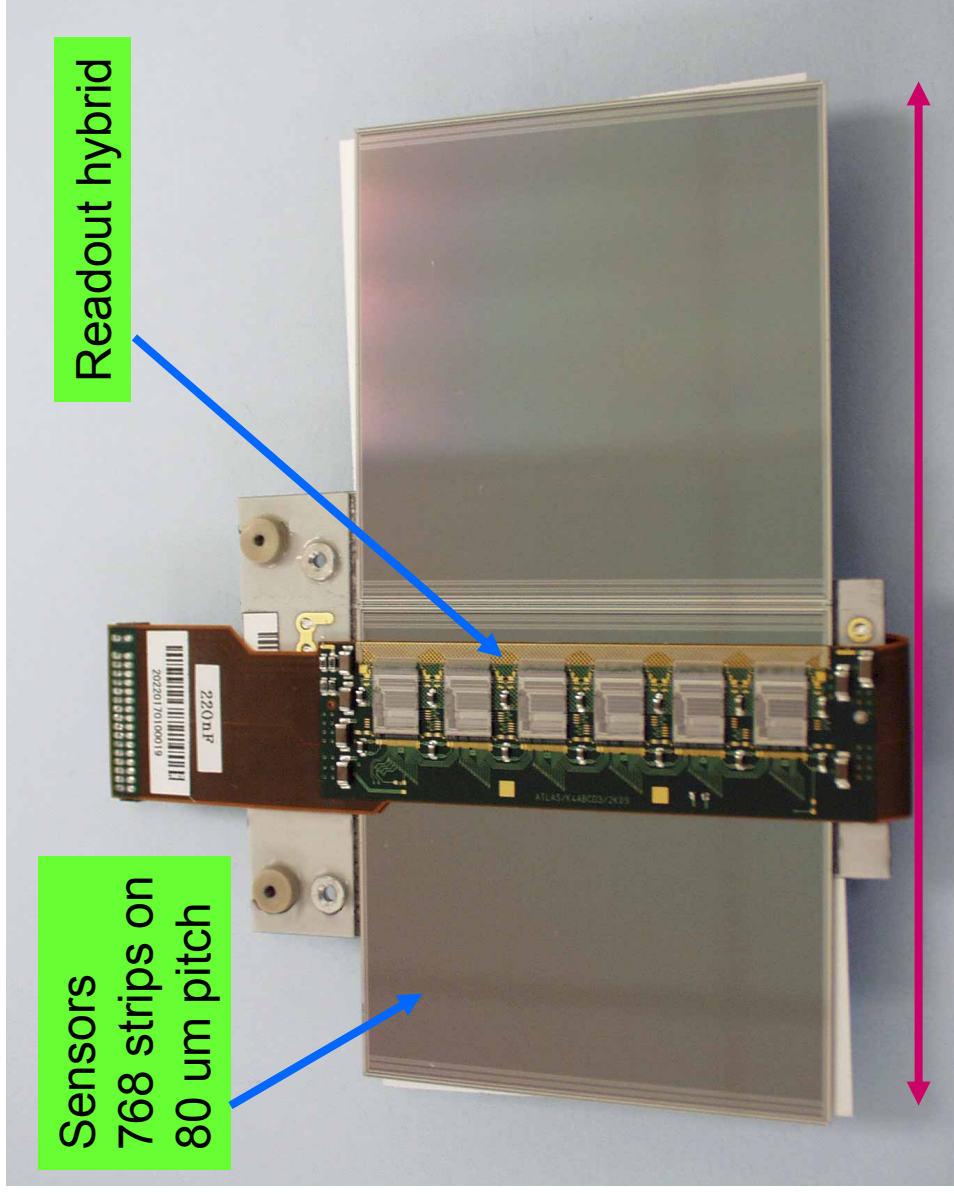
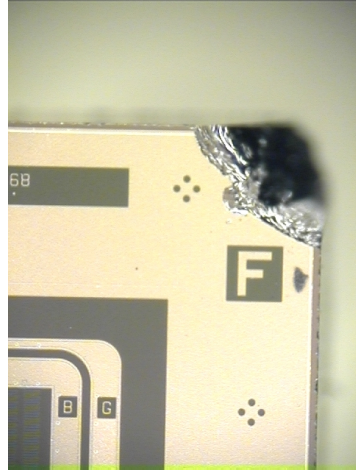
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Major Sound Archives

- The US Library of Congress 2.5M recordings
- The British National Library: 2.5M recordings
- The Stanford Archive of Recorded Sound: 250K recordings
- The New York Public Library: 500K recordings
- The Berlin Phonogramm-Archiv: 145K total, 30K cylinders
- The Vienna Phonogramm-Archiv: 50K
- The Belfer Archive at Syracuse University: 340K recordings
- The Yale Historical Sound Collection: 160K recordings
- The Edison National Historical Site (NJ, USA): 37K cylinders
- Discoteca di Stato, Rome
- Swiss National Sound Archive
- [Most governments maintain a national sound archive of some sort....](#)

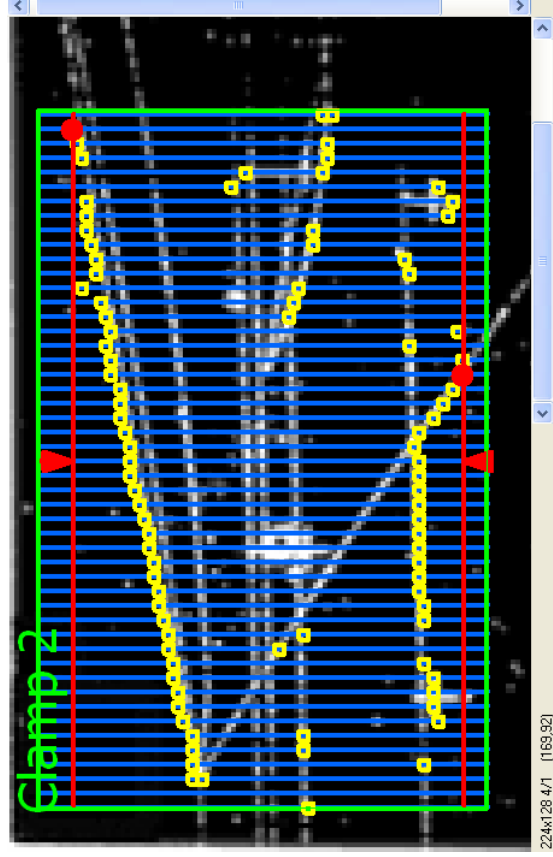
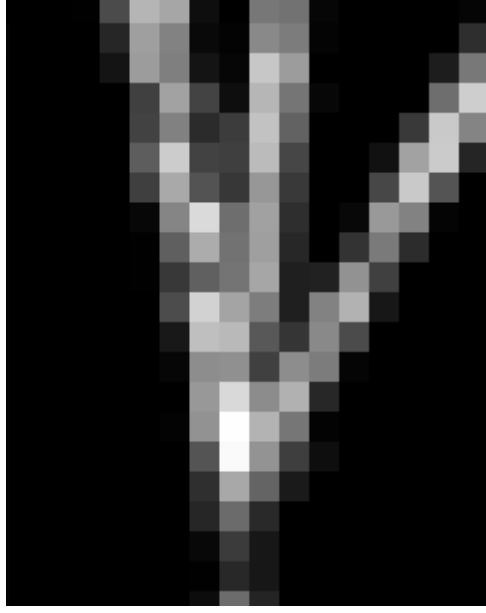
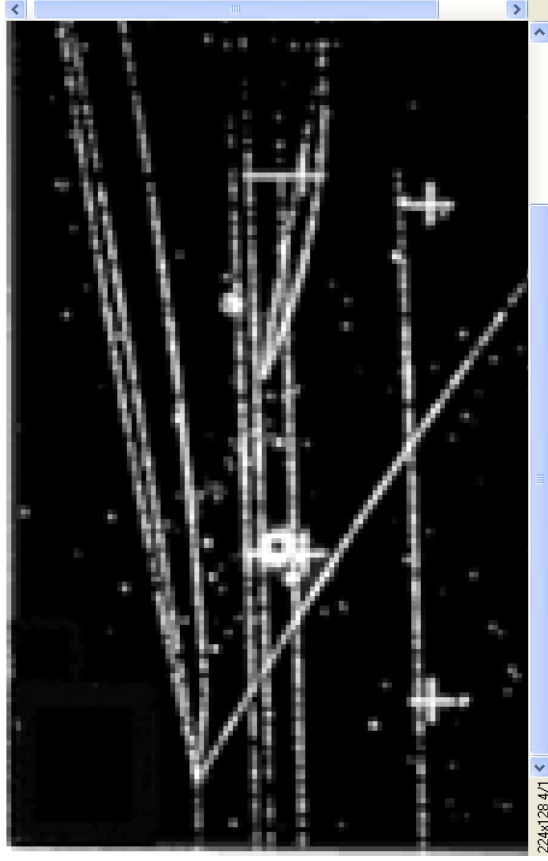
Optical Metrology of Sensor Array



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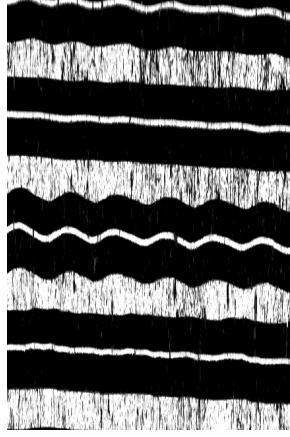
Archives and collections now transfer recordings to more stable and accessible formats using modern stylus players and conservation protocols. Requires contact to the media and audio professionals.

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. No contact to the record is required.

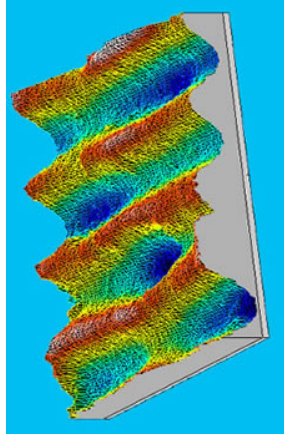
Non-Contact Digital Imaging

- 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

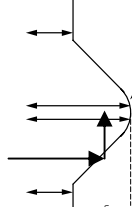
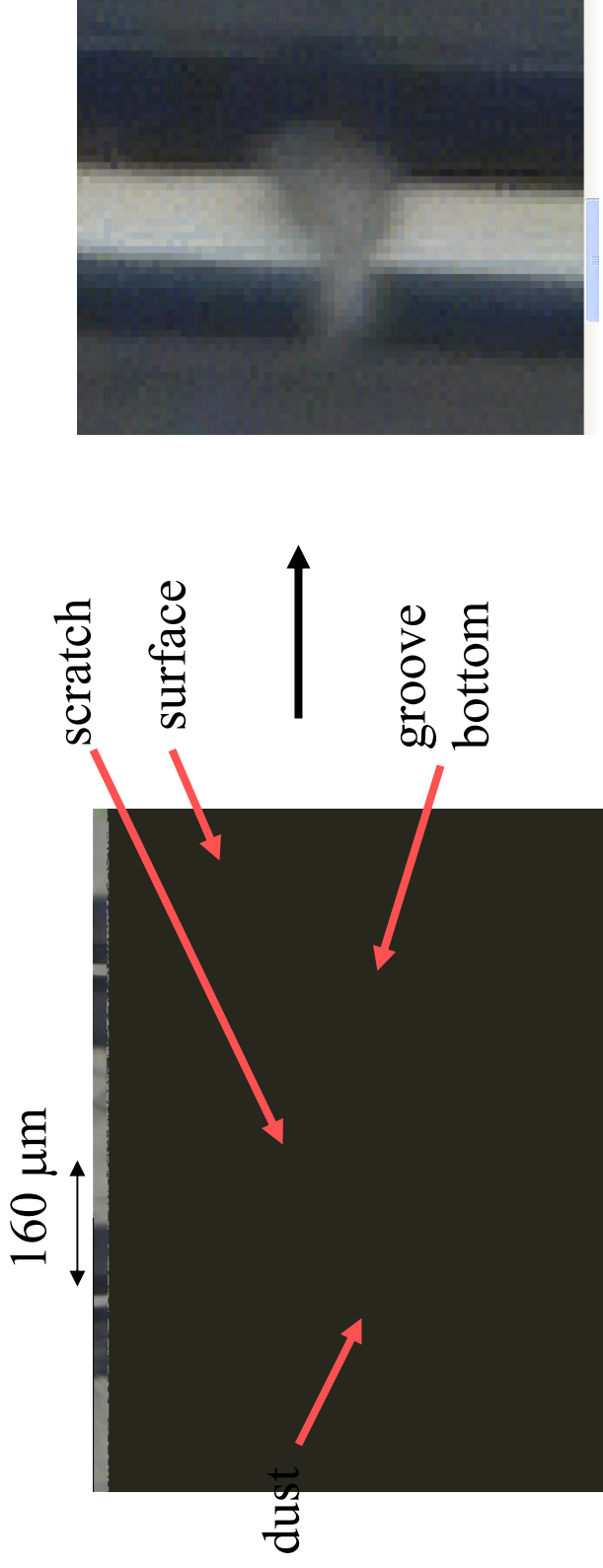


Surface profile of a wax cylinder:
A three dimensional image “3D”
is required for vertical cut grooves¹⁴

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

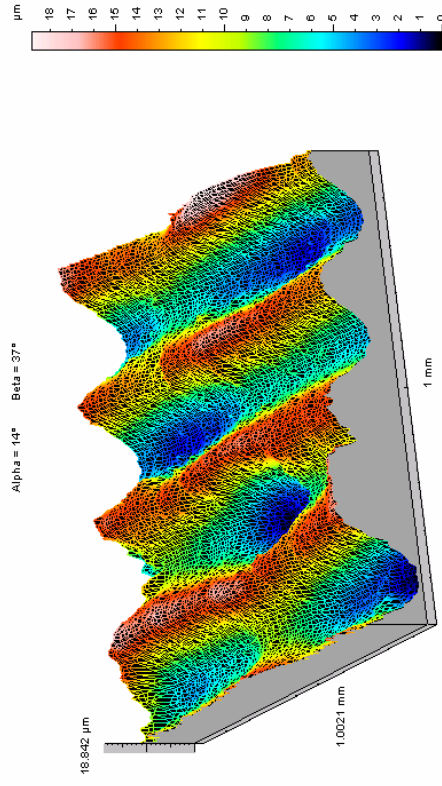
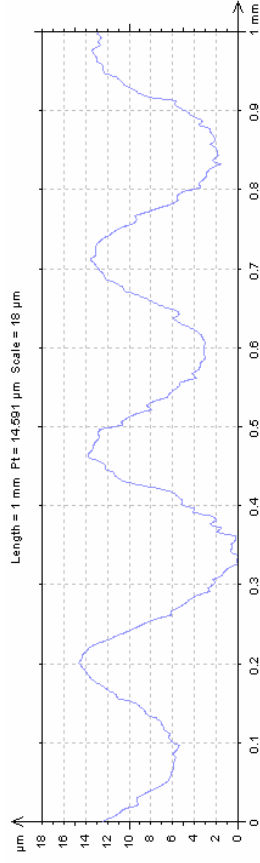
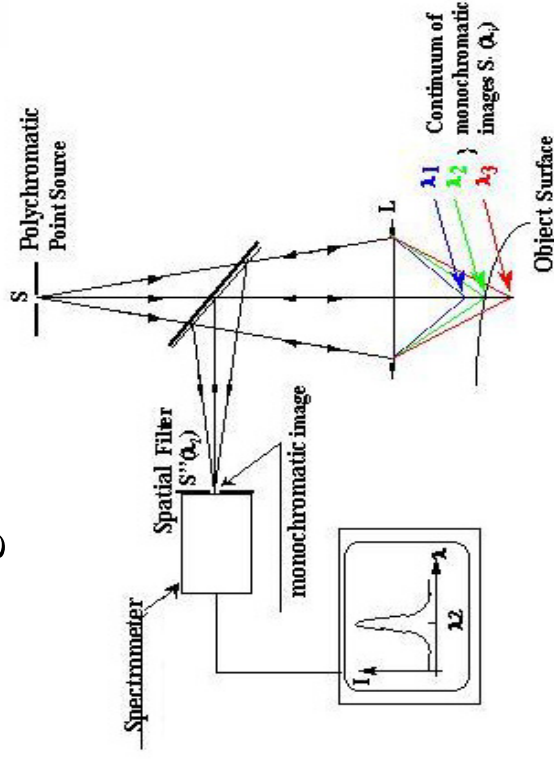


- Suitable for disc with lateral groove
- Require 1 pixel ≈ 1 micron on the disc surface
- Coaxial illumination

3D Imaging: Confocal Scanning Probe

Required for cylinder
with vertical groove
modulation.

Point by point scan
0.01 degree = 96 KHz



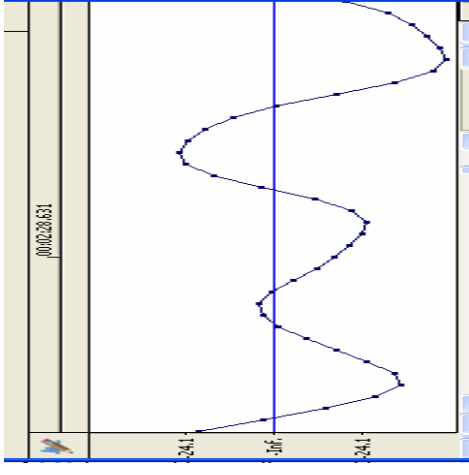
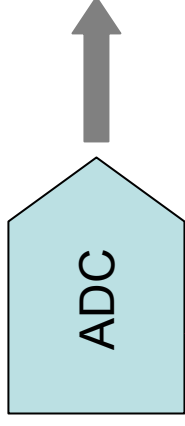
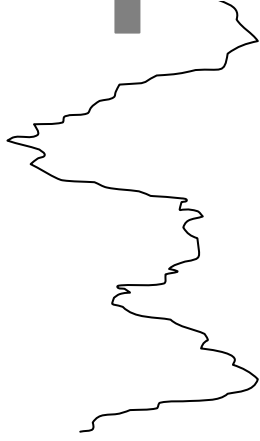
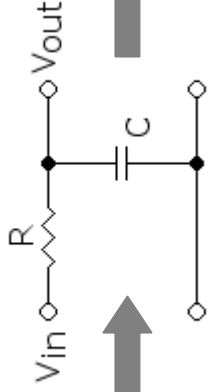
Surface of an Edison cylinder

Up to 4000 pts/second

Depth Of Field	20 μm	80 μm	300 μm	350 μm	3 mm	6 mm	10 mm
Working Distance	0,6 mm	2,1 mm	4,5 mm	12 mm	38 mm	53 mm	65 mm
Z Axis Resolution	1 nm	3 nm	10 nm	10 nm	100 nm	200 nm	300 nm
Accuracy	10 nm	30 nm	0,1 μm	0,1 μm	1 μm	2 μm	1 μm
Spot Diameter	1 μm	2 μm	4 μm	1,5 μm *	10 μm	40 μm	50 μm
Lateral Resolution	0,5 μm	1 μm	2 μm	0,75 μm	5 μm	20 μm	25 μm
Numerical Aperture	0,69	0,57	0,5	0,5	0,26	0,26	0,17
Max Angular Slope (+/-)	44°	35°	30°	30°	15°	15°	10°

Analog waveform

Low-pass filter
 $f_0 < f_{\text{sample}}/2$



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

Pixelized image determines sampling

Natural segmentation
by pixel size,
magnification,
resolution

Easily time sample to 300 KHz

Amplitude sampling set by
resolution

~0.3 microns / 250 microns max
Not 16 bits!!

Time

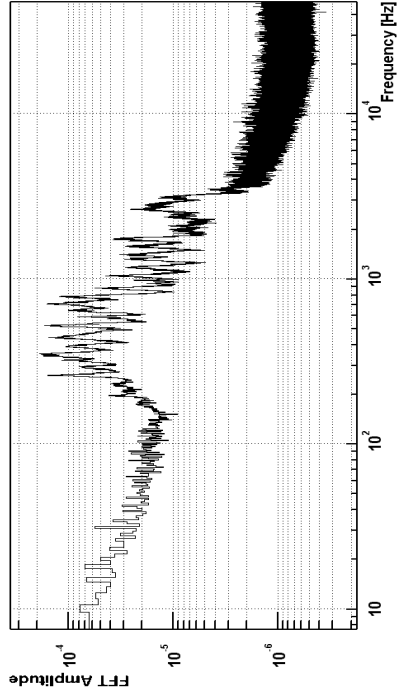


Amplitude



Issue of Aliasing

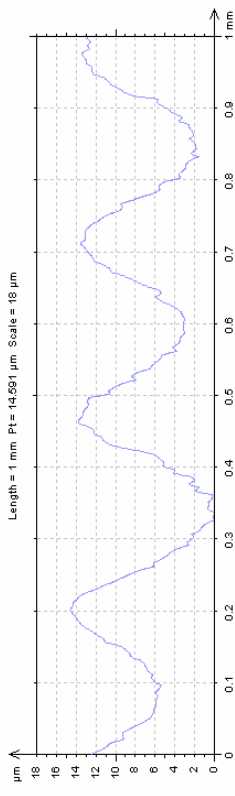
- Sampling theorem
 1. Sample at $2*f$ where f is highest frequency of interest
 2. Apply low pass filter above f to prevent aliased components appearing in data unless noise above f can be neglected.
- In optical approach sampling is done by pixelization of image.
 1. High sampling frequency
 2. Use of pixel size to achieve effective low pass filtering?



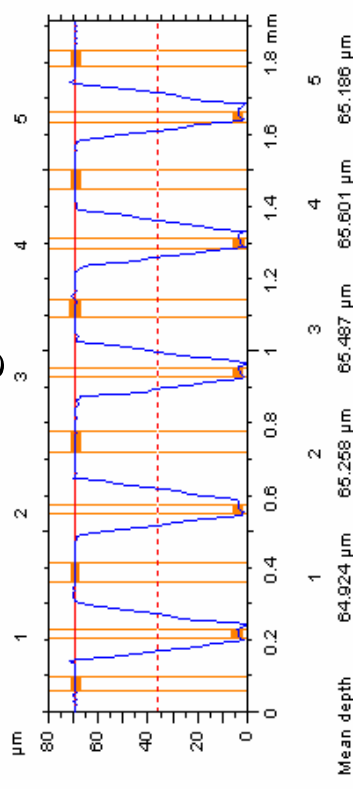
Speed and Data

- 2D scans for lateral discs
 - Fast camera: ~10 min for 78 rpm disc
 - 50 Mb / 1 s of raw images
 - 1.5 Mb / 1 s processed
 - 88 Kb / 1 s audio (44/16)
- 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

Vertical groove

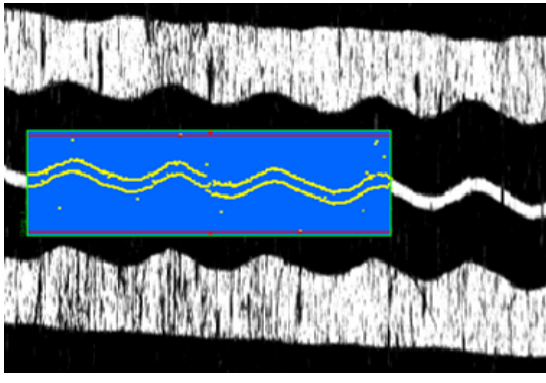
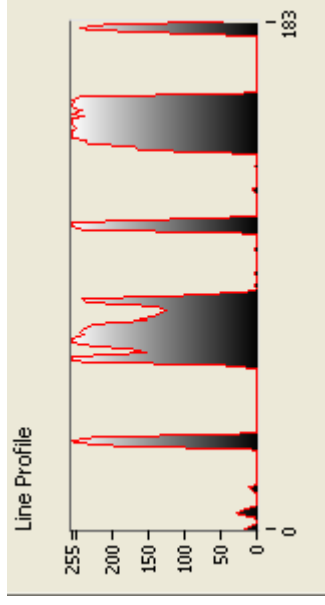
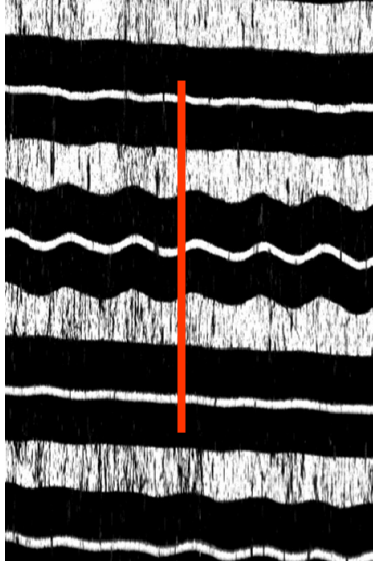


Lateral groove



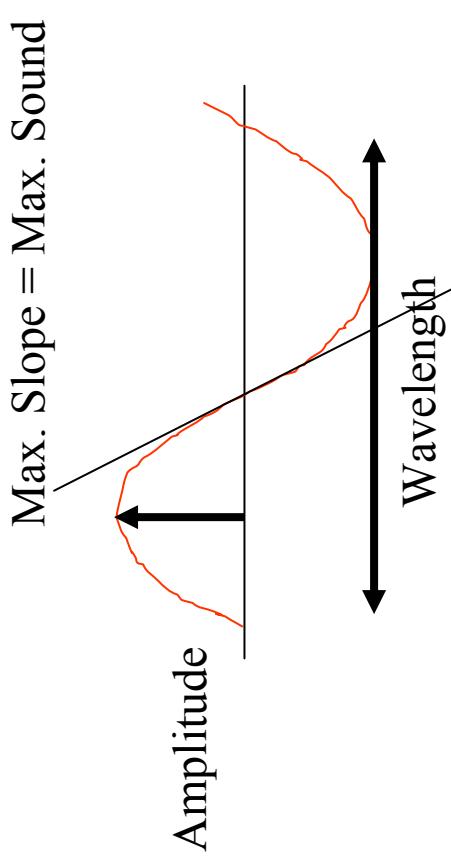
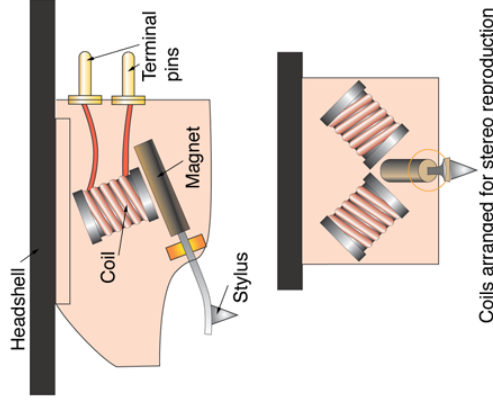
Key 3D issues are slope and depth

Image Analysis (2D case)



What is the relationship between “groove” and sound?

Electro-magnetic case



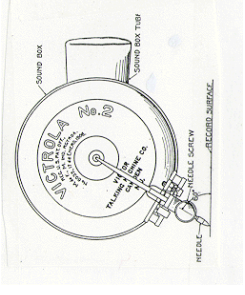
$$\text{Sound} = \text{Stylus Velocity}$$

$$A_p = \frac{v_p}{2\pi f}$$

(“constant velocity condition”)

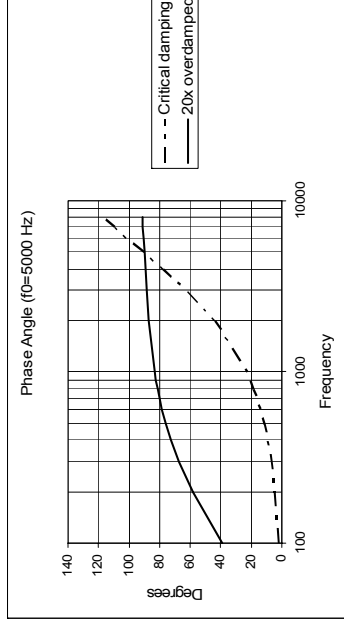


Acoustic Case



- 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



Numerical Differentiation and Filtering

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

$$= \frac{1}{N} \sum_{k=0}^{N-1} (-ik\Omega) M(k) C(k) e^{-ik\Omega nT}$$

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

The filtering factor:

Perform the differentiation and filtering in a single

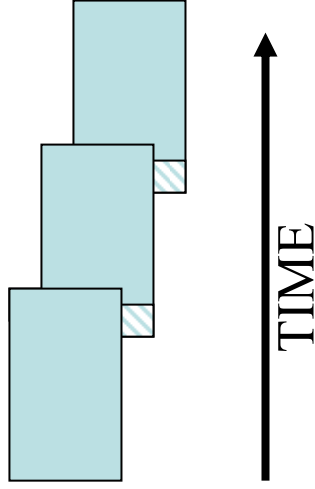
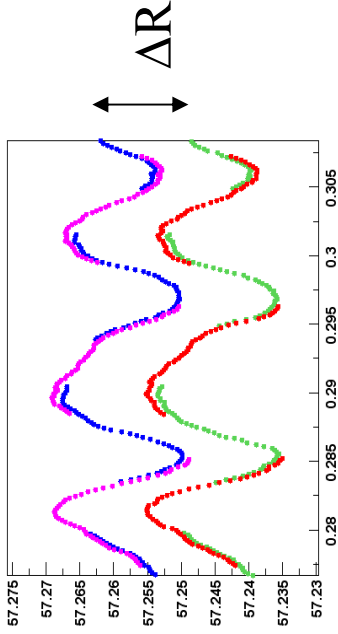
processing step by:

- Doing FFT transform
- Applying $(-ik\Omega) M(k)$ factor
- Doing reverse FFT transform
- Or simpler point by point methods

Comparison

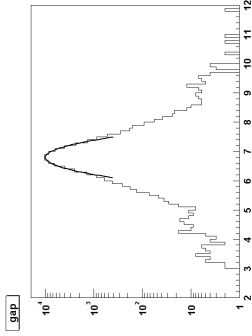
- ✗ Data intensive
- ✗ Scanning speed (particularly 3D)
- ✗ Is fidelity sufficient?
- ✗ Powerful restoration methods for audio already available
- ♪ Non-contact
- ♪ Robust – wax, metal, shellac, acetates...
- ♪ Effects of damage and debris reduced by image processing
- ♪ Re-assemble broken media
- ♪ 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.

Groove trace data, R[mm]-vs-phi[rad]

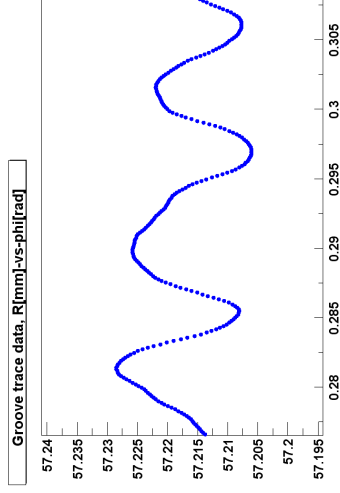


Measurement spacing along
time axis ~ 66 KHz

ΔR distribution

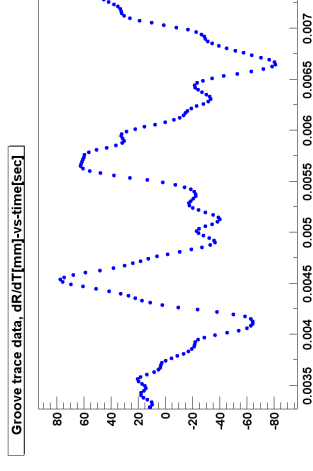


Width across
groove bottom



Measure slope
at each point
(stylus velocity)

Align
Average
Filter using $\Delta R < \text{cut}$



Sound Comparison

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



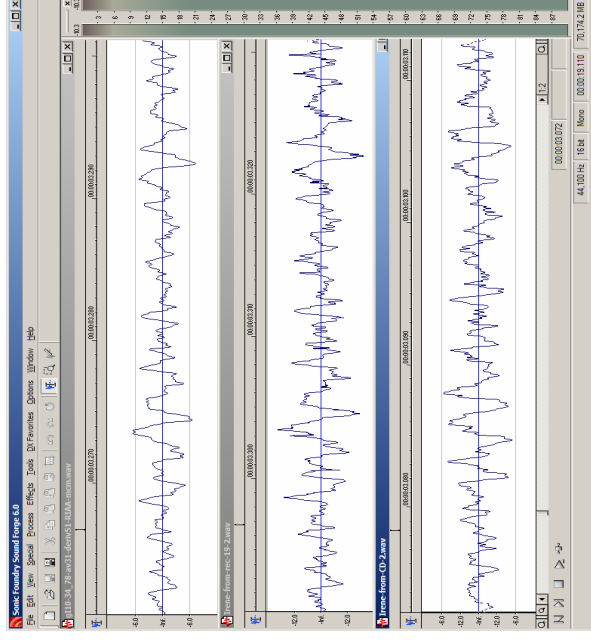
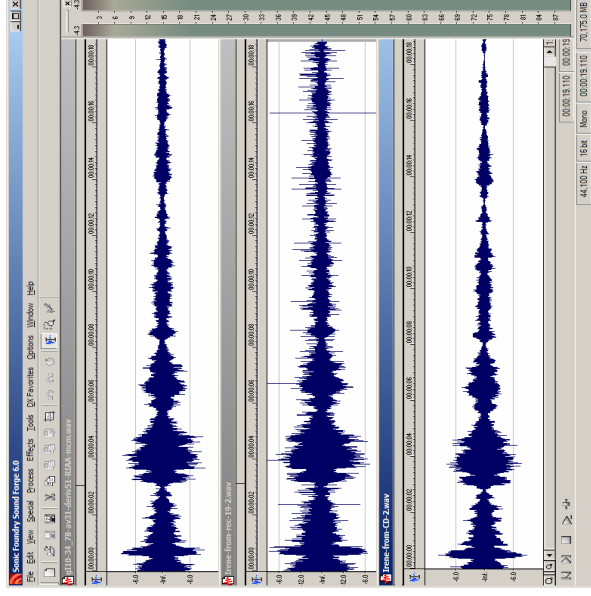
optical readout.



mechanical (stylus)



CD re-mastered tape.



Bernard Hoffman/LIFE ©Time Inc.



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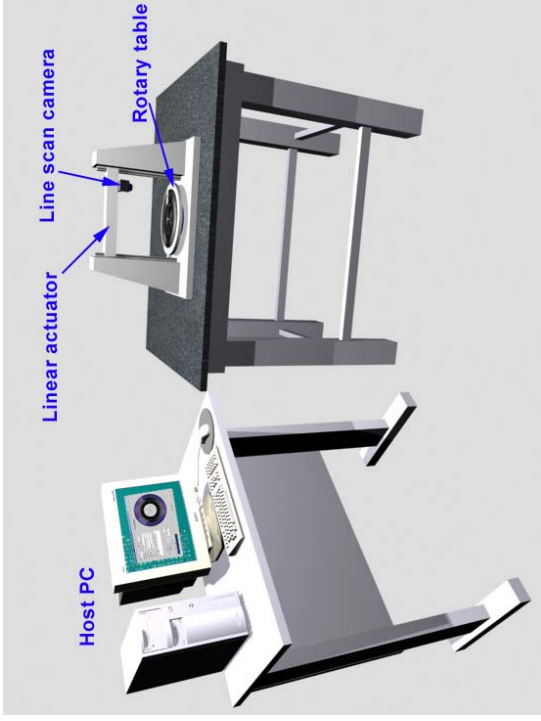
29

Projects Underway

- IRENE: a fast 2D optical scanner for disc records
 - Digital access to the most common media + special formats
 - Under construction for the Library of Congress
- 3D scans on “Edison” cylinders
 - Preservation and restoration of early and damaged recordings
- 3D scans on plastic dictation belts
 - Feasibility study for preservation transfers of damaged media
(Dallas PD recordings, Presidential collections)

I.R.E.N.N.E.

Image, Reconstruct, Erase Noise, Etc



- ~1 year development and construction
- Projected scan time 5-15 minutes
- User friendly interface
- Emphasize throughput and diversity (access)
- Provide statistical measures of media condition
- Production-like machine and test-bed for future development

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LBL Instrumentation

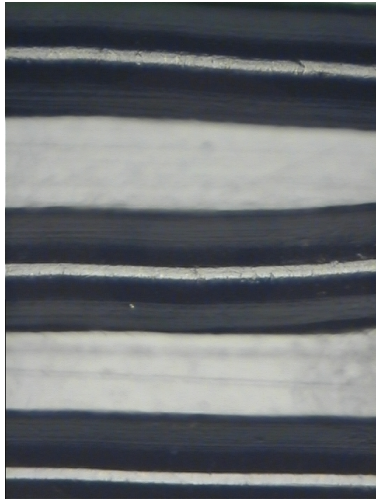
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Testing and Validation Phase

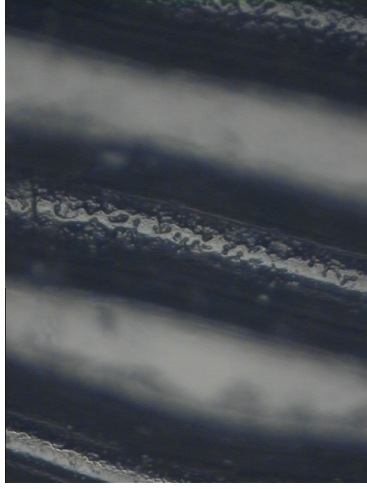
- LC is to receive machine in 2006
- Machine to be tested on a significant sample of media by LC staff
- Results to be documented and disseminated
- Possibility of a follow-on stage
 - Upgrades to software (easy) or hardware
 - Expanded media study

Media Condition Survey on LC Samples

good 65%



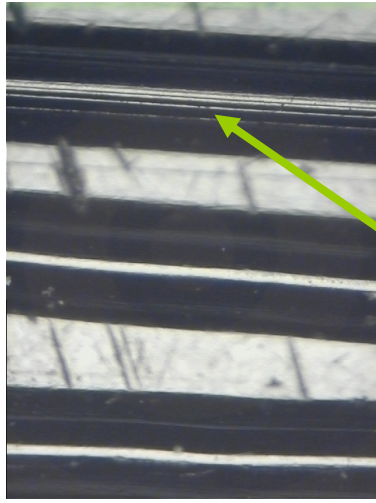
poor 10%



good lacquer

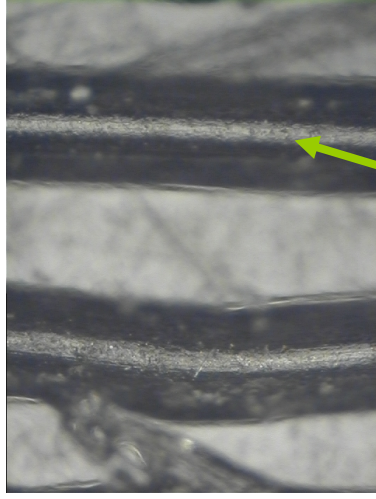


fair 25%



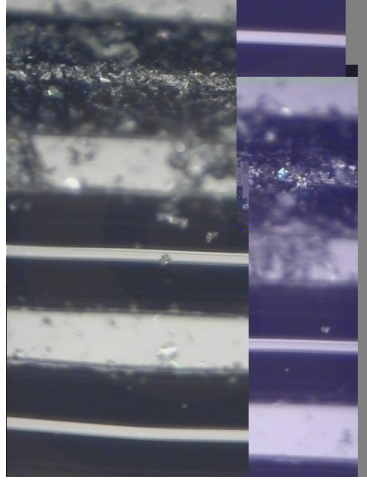
Multiple edges

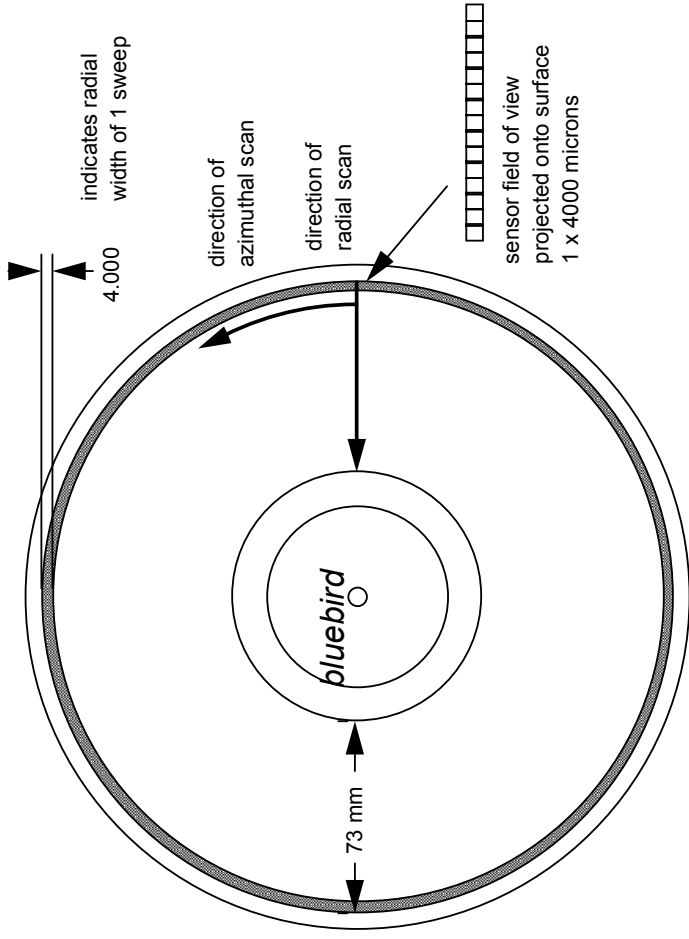
fair



Rough groove bottom

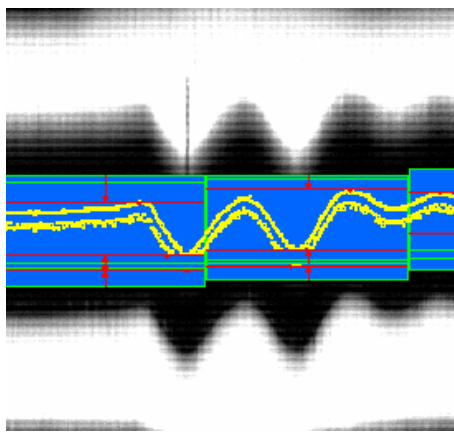
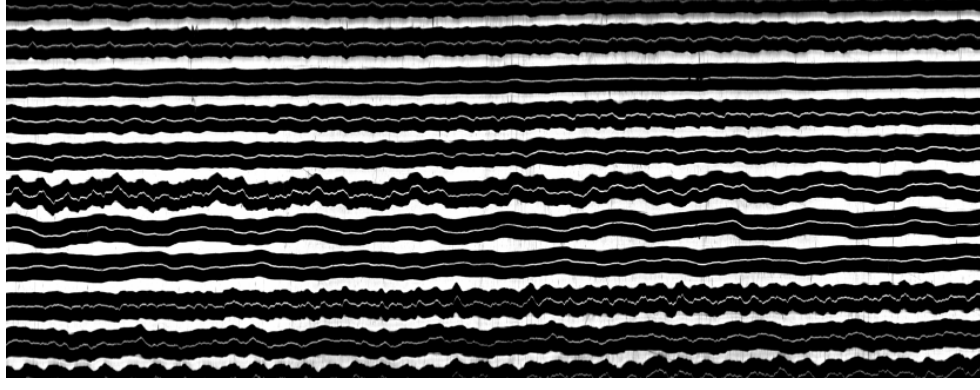
exudated lacquer

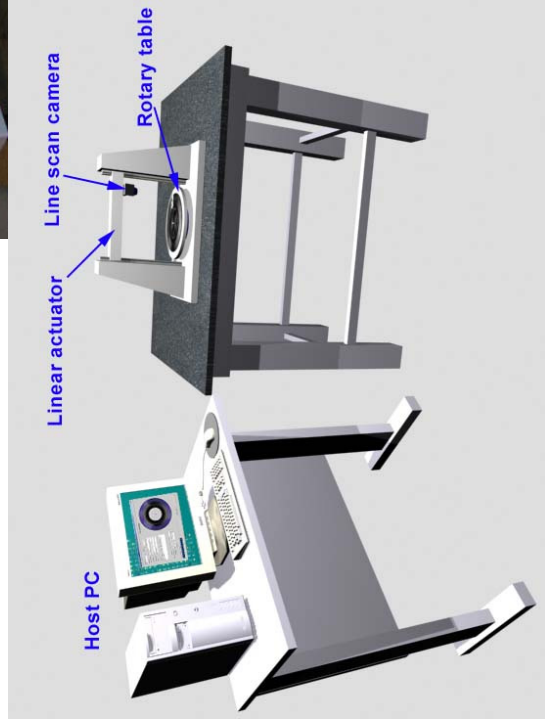
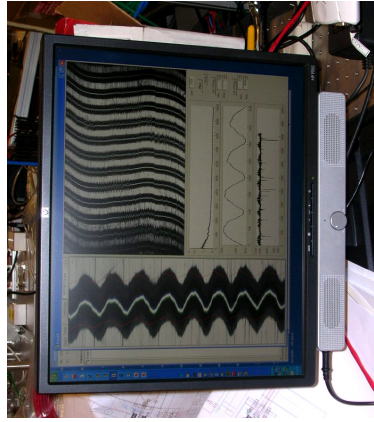




- 6000 pixels@15 K lines/s
- 7.6 x 10⁵ lines/outer ring
- 390 KHz max sampling
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.

Line Scanning: disc is in motion





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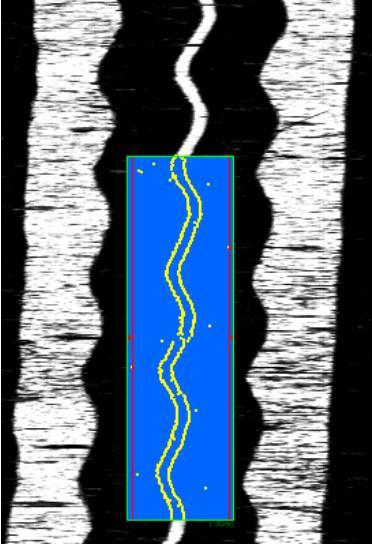
78 rpm shellac disc



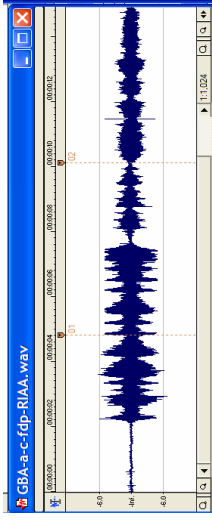
Optical line scanner: turntable with disc below, optics mounted vertically (“IRENE”)



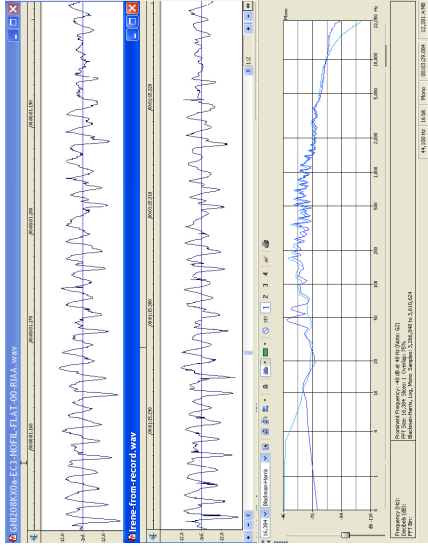
Image of groove segment

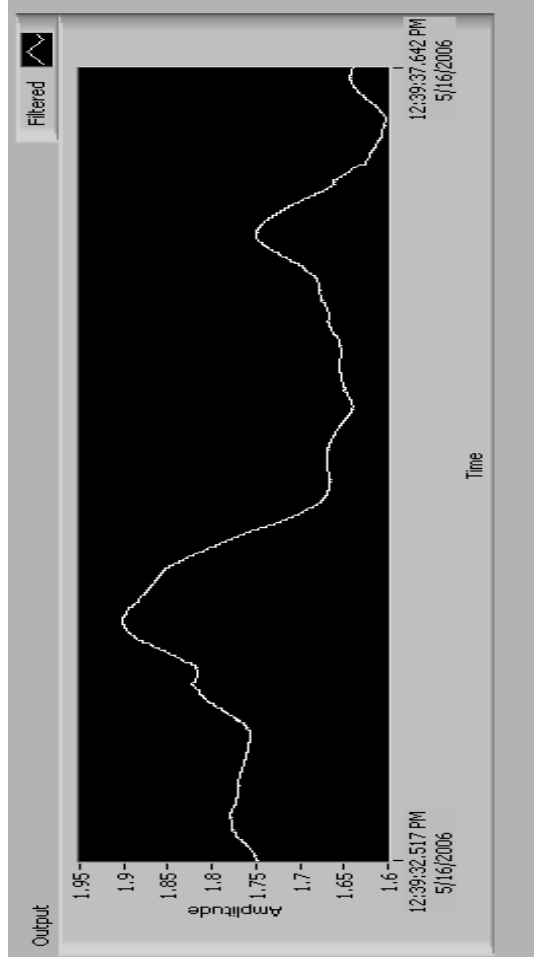
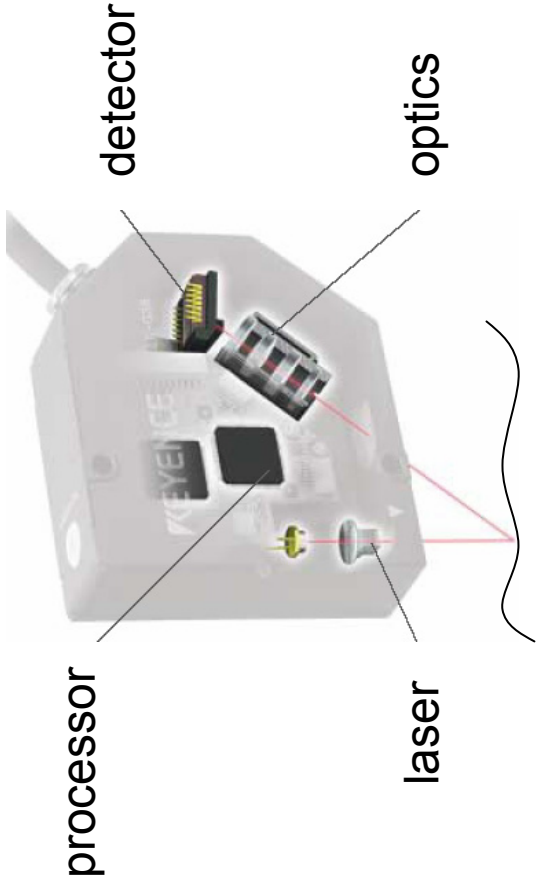
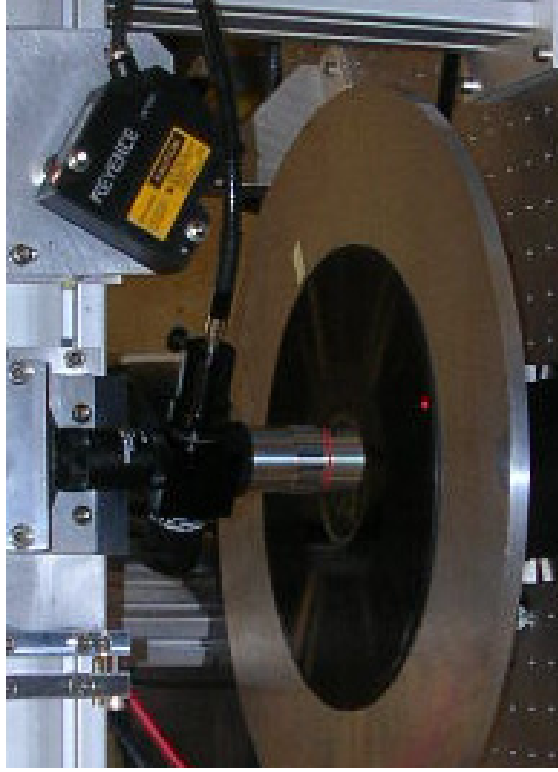


Mechanical features of groove extracted from image



Audio waveform derived from metrology data

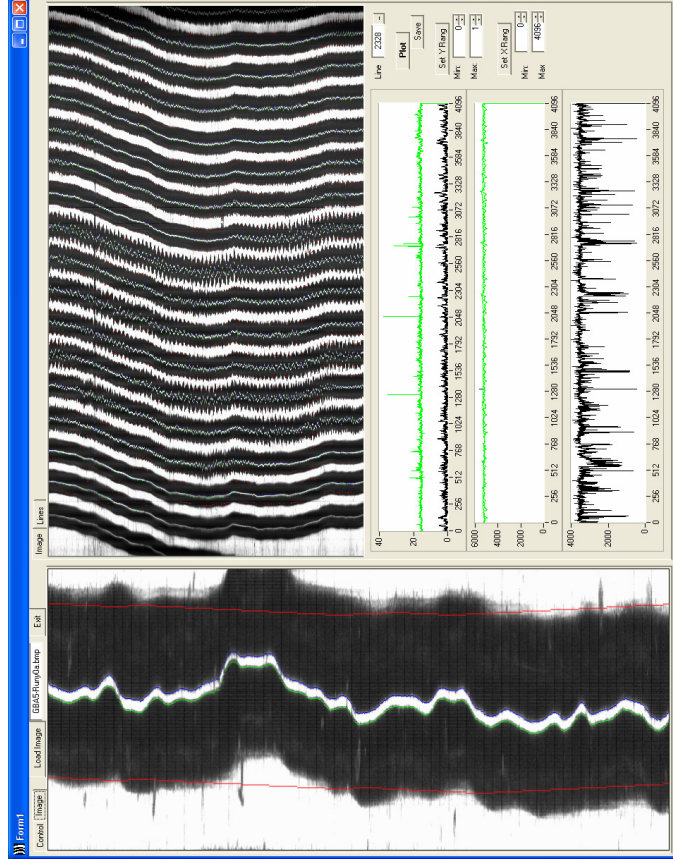




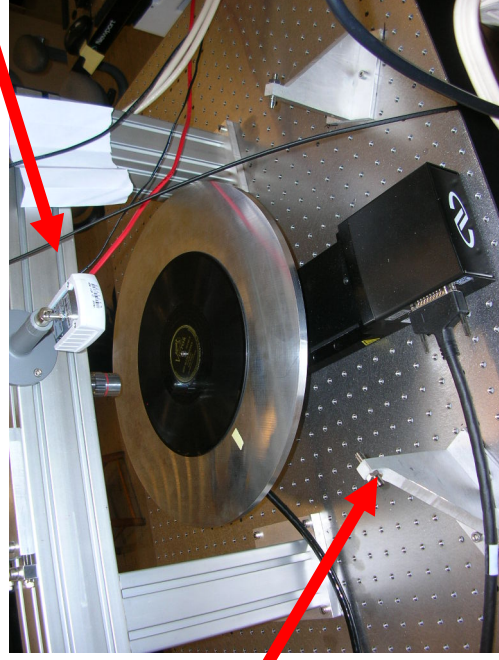
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Eccentricity control



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Label camera

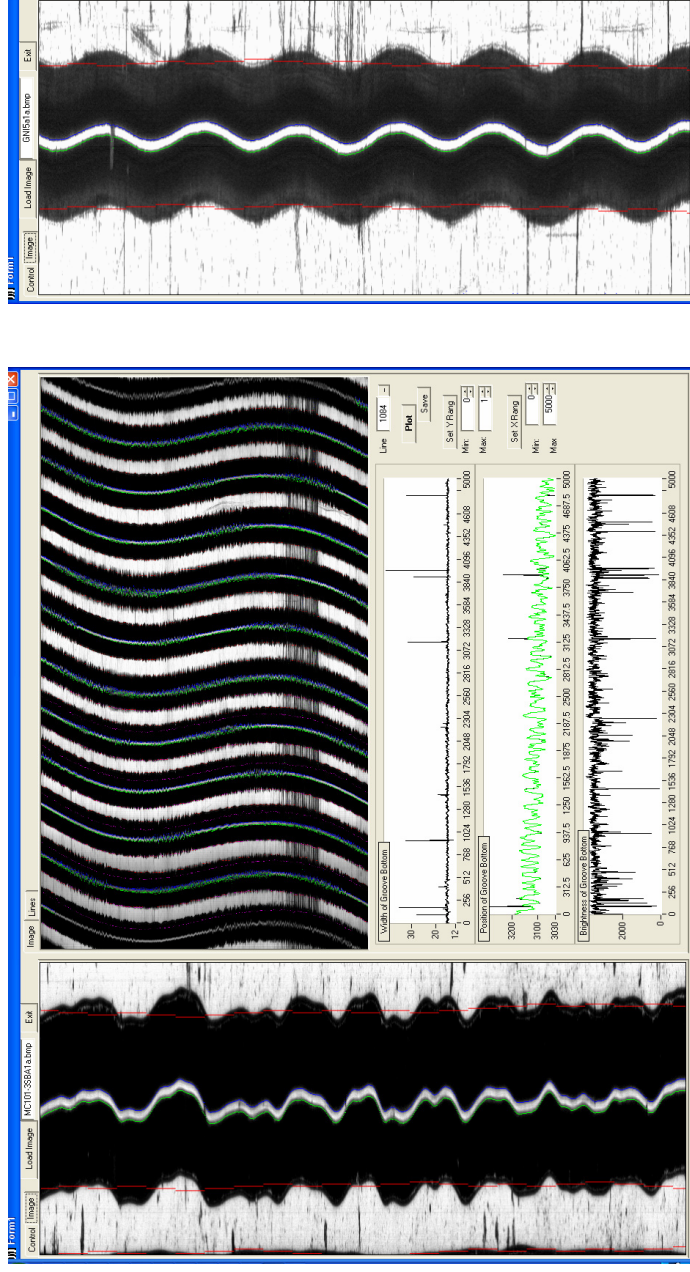


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Status

- 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
 - Frequency coverage OK
 - Restoration, filtering aspects still under study

Groove Images



Poor quality
shellac, acoustic
recording

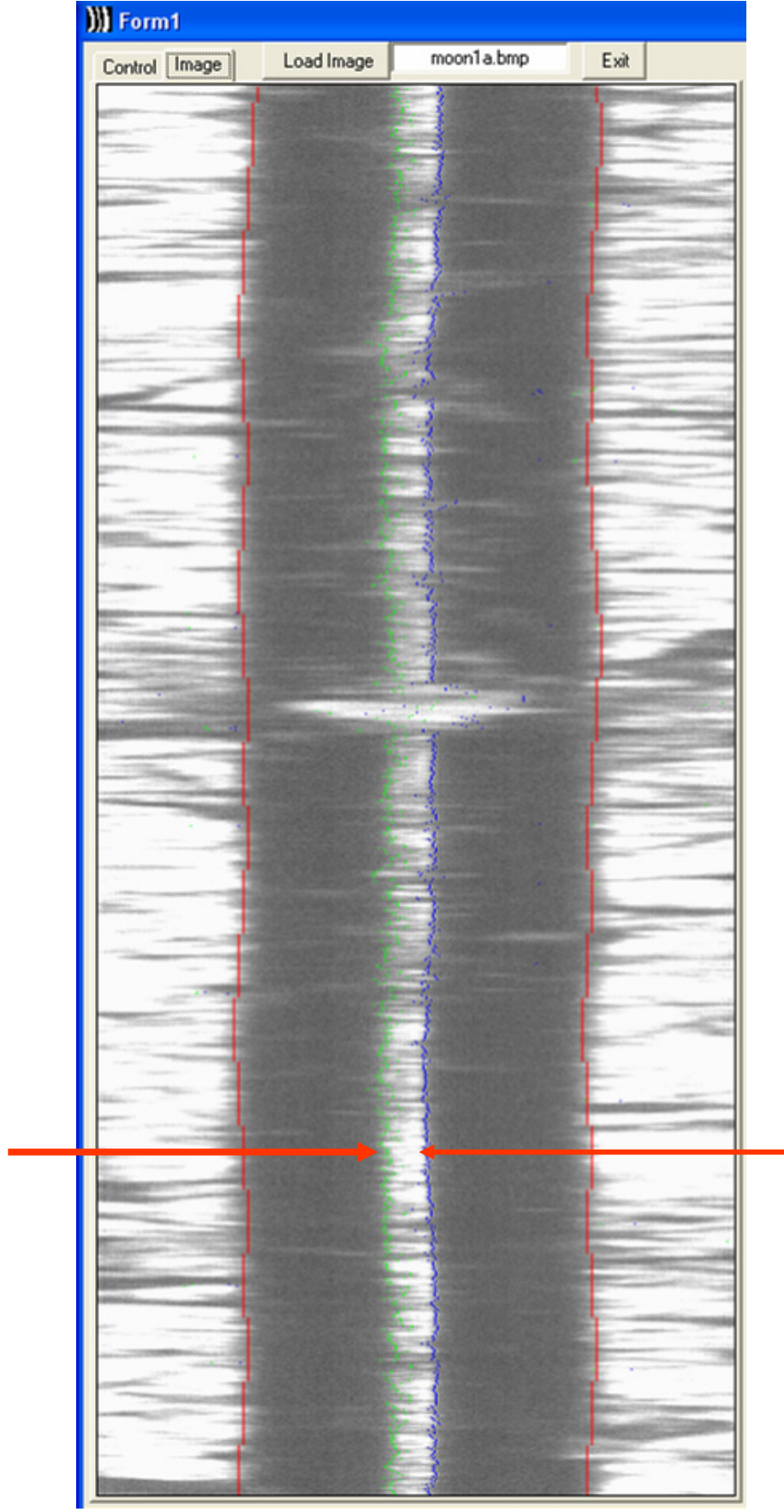
Shellac with
moderate wear

Lacquer disc

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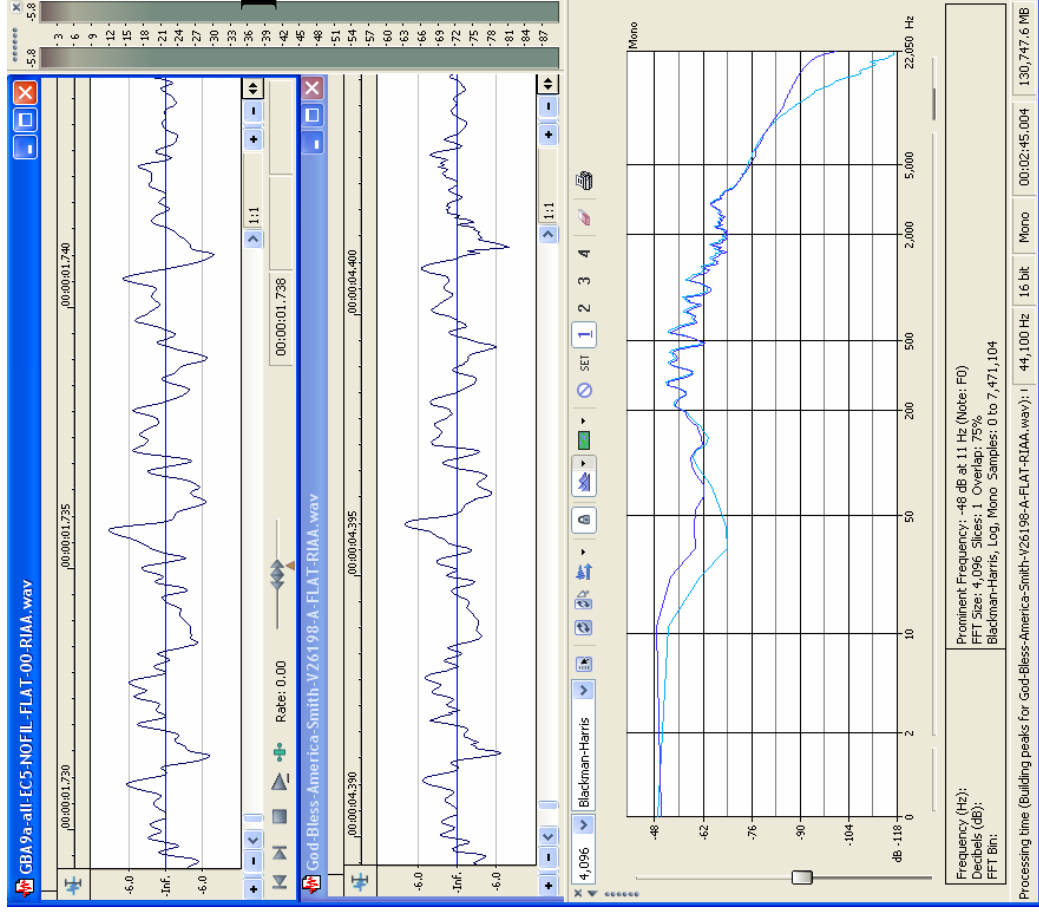


God Bless America: Kate Smith



Shellac with moderate wear,
RIAA curve applied

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IRENE



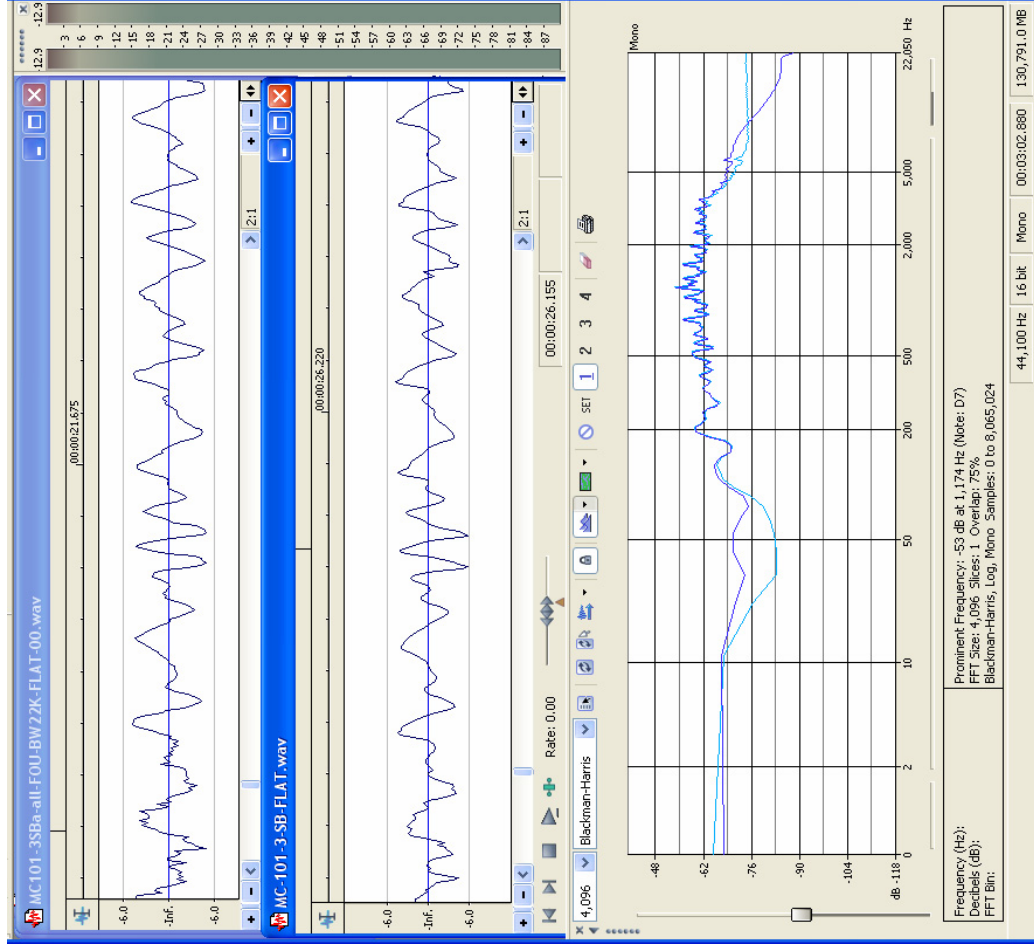
stylus

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Unknown studio take ~1940's



Lacquer disc, FLAT playback



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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

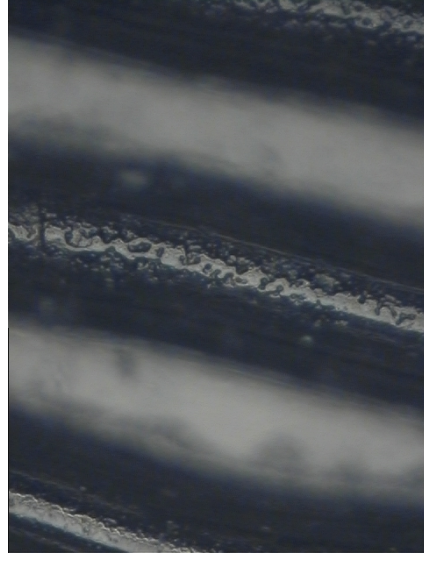
In the Evening by the Moonlight
Performed by Columbia Stellar
Quartette, Columbia A2683, 1918



Stylus version



IRENE test scan



Interesting Lacquer Discs



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



78 rpm acetate,
Theos Bernard,
interview, 1929





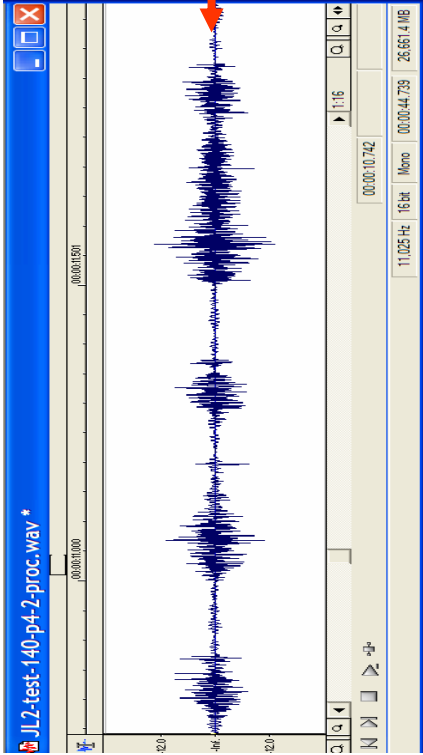
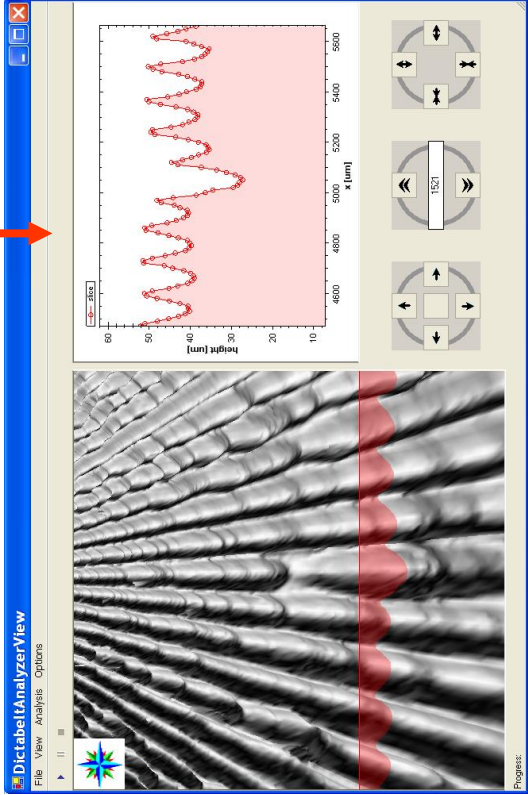
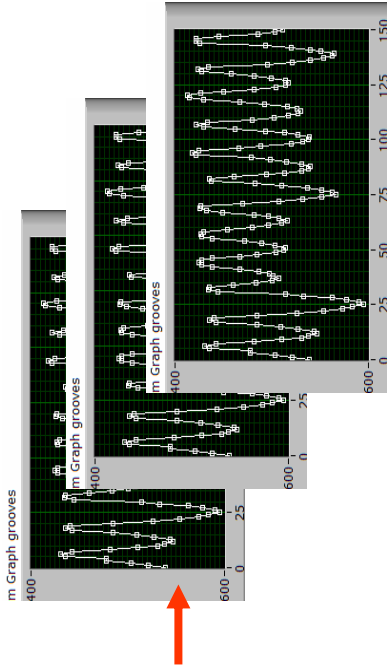
Cylinder Scans

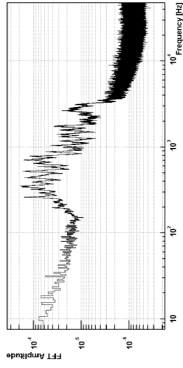
- Cylinder History
 - 1877 Aluminum foil
 - 1885 Soft wax for original recordings and dictation
 - 1902 Hard wax molded, commercial
 - 1908 Cellulose molded, commercial “Amberols”



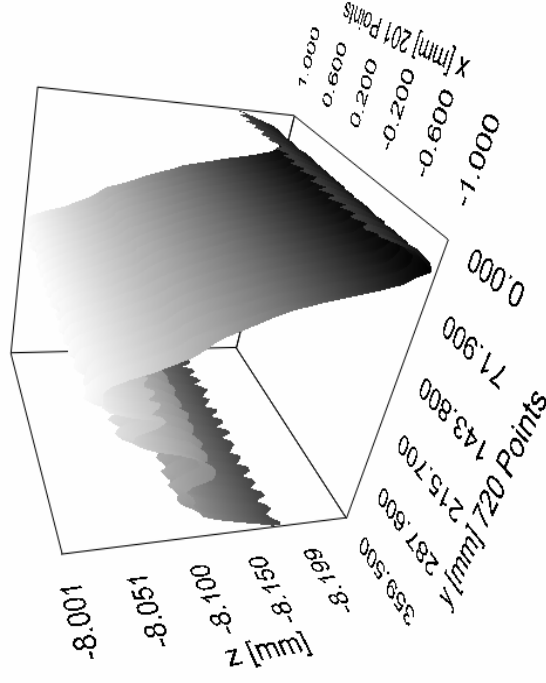
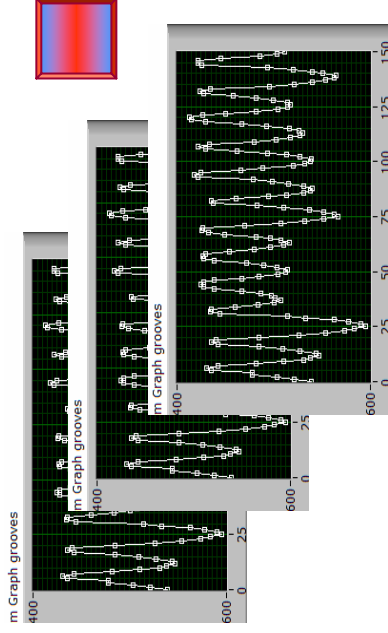
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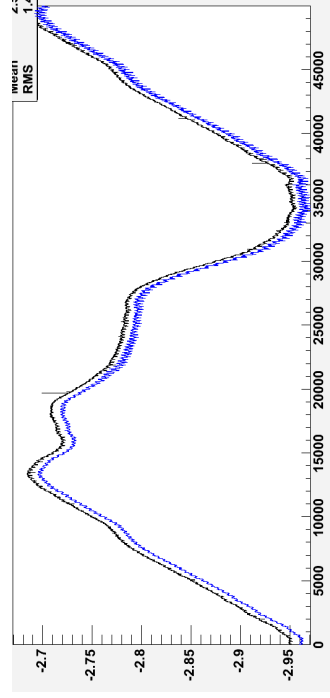
Sample at 96KHz to minimize effect of aliasing



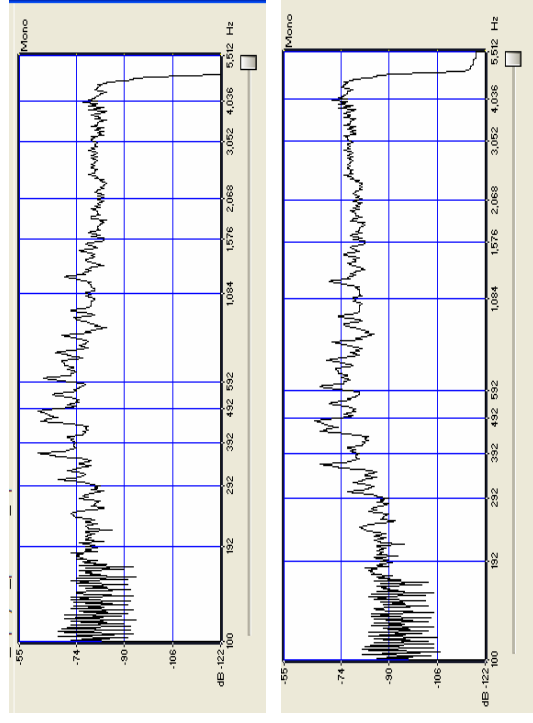
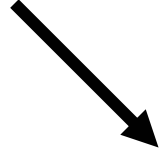
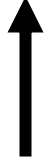
Sequential axial scans

Subtract valleys from ridges to correct for overall shape

(Ridges provide (approx), geometrical reference)



d/dt



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

Sound Comparison

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



• Stylus



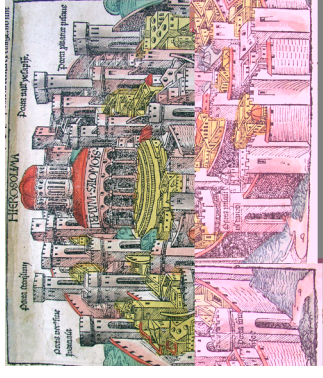
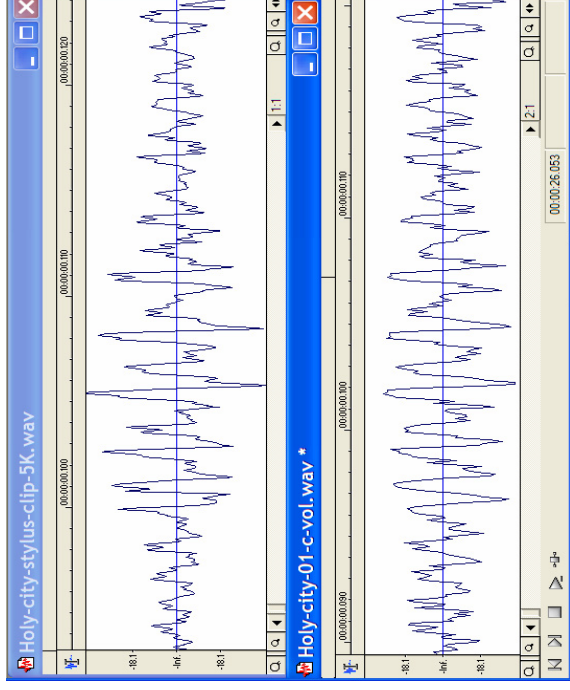
• Optical



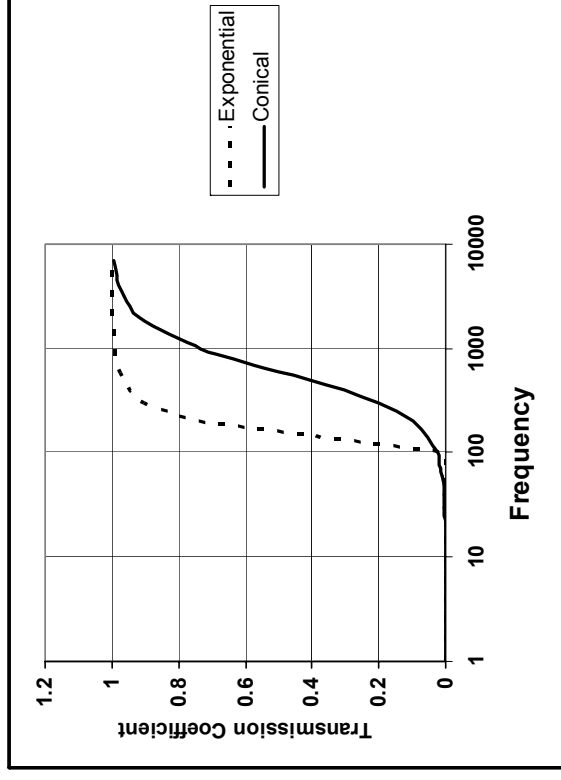
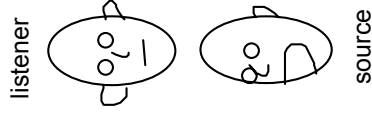
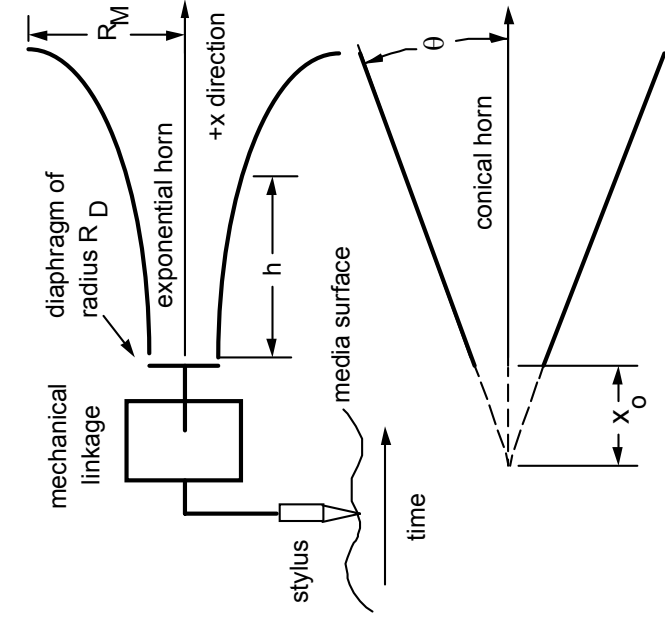
• Optical + filter + EQ



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Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.



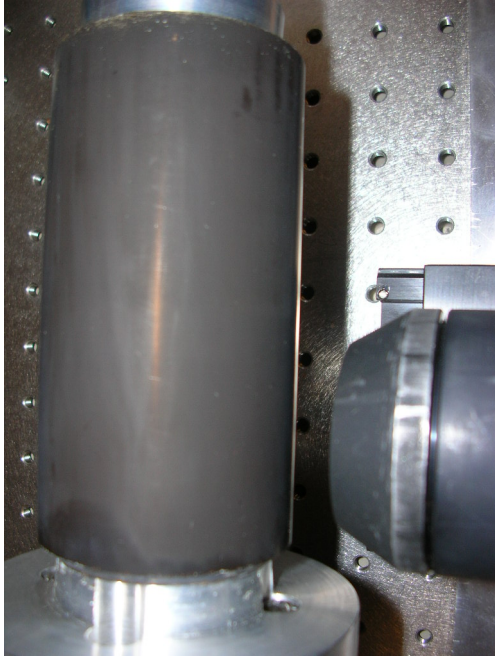
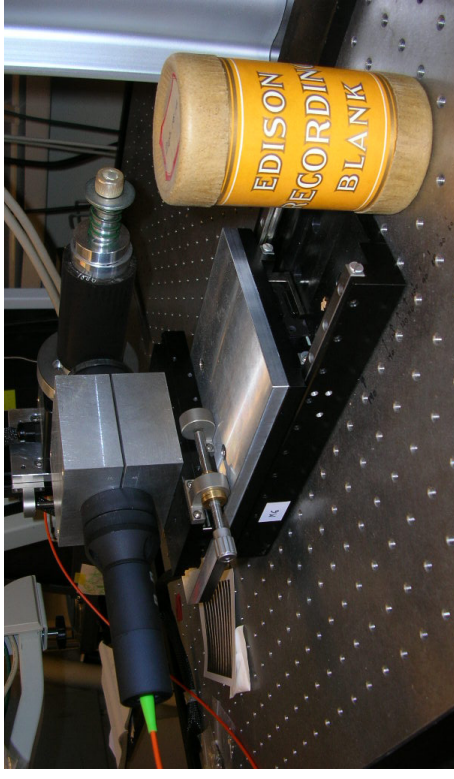
Damaged or Delicate Cylinders

- 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

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.





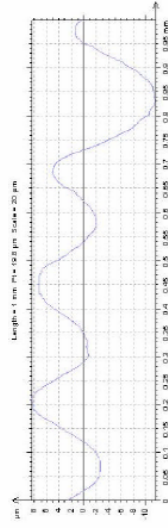
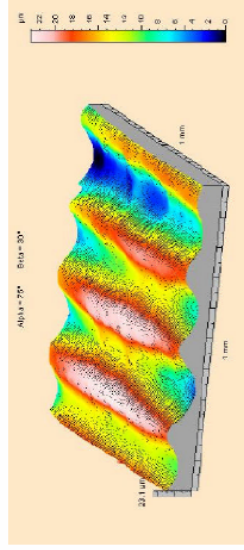
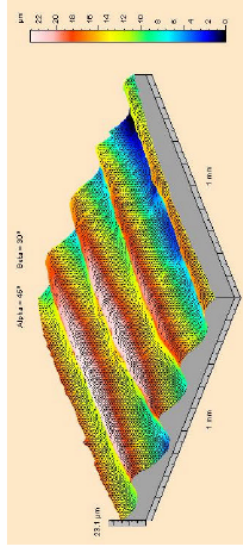
Ishi at Deer Creek

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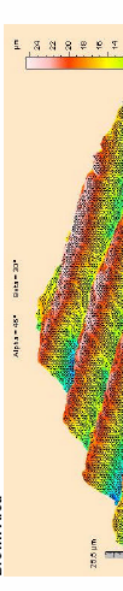
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Surface Damage = Sound Degradation

Clean Area



Brown Area



London Wax Cylinders



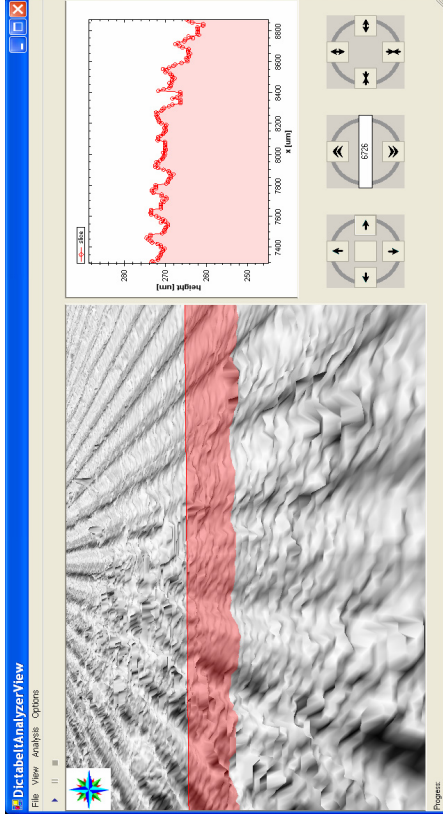
Jack and Charmian London



JL's Dictaphone machines
from the JL State Park

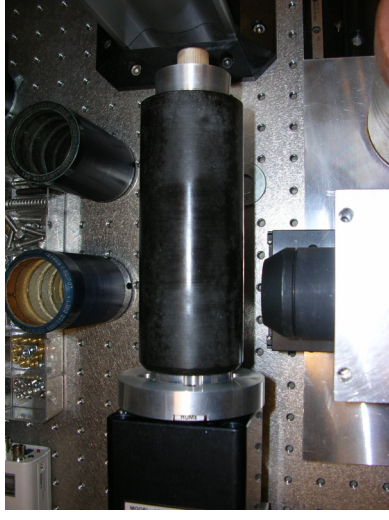


1st cylinder from JL house
with mold growth visible



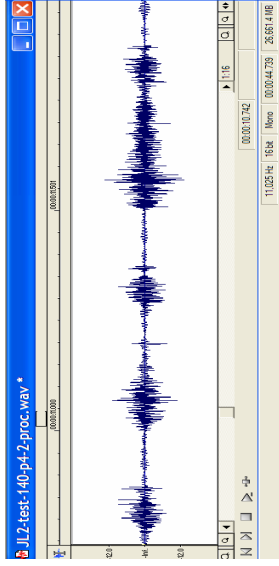
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1st Cylinder on 3D scanner

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?](#)

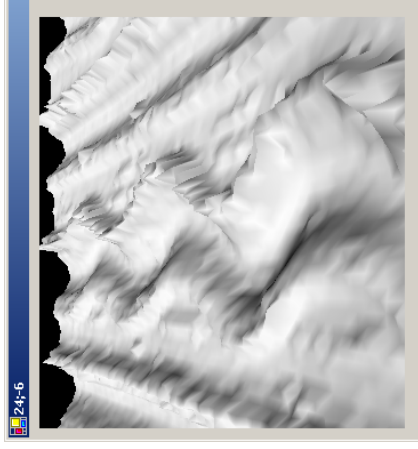
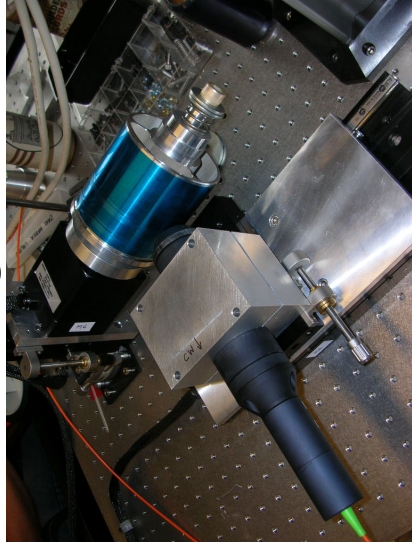
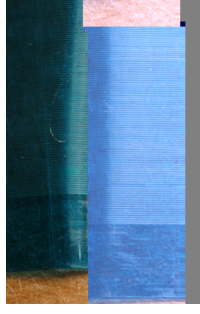


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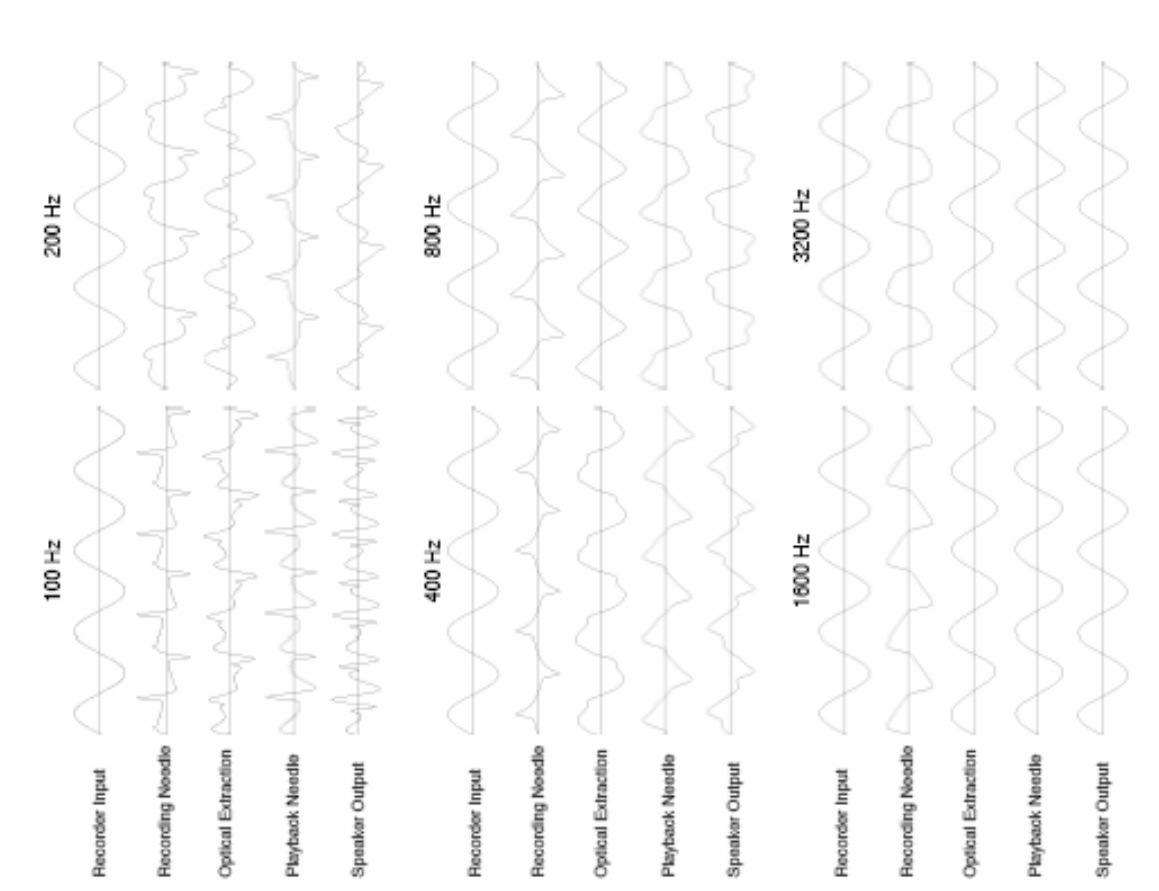
Dictation Belt Scanning

- 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



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From Top Quarks to the Blues

Particle Tracks Tune Up Music

Physicists Seek to Digitize Music, Restore Media

Using high-energy physics to preserve old records

Scientists find new way to play old records

Optical Metrology Reconstructs Audio Recordings

[From the Higgs Boson Particle to Leadbelly](#)

Teilchenphysik im Dienste des Kulturerbes

Teilchenphysiker retten das musikalische Erbe der Menschheit

Particle Physics Recovers Music From the Past

New technique preserves old sounds

Digitizing groovy records

De la Física a la Fonografía

Physiker retten Schellack-Aufnahmen

Particle physicists to help restore old audio recordings

How to listen to old records in the 21st century

Particle physicists rescue rare vinyl recordings

Φυσικοί βρίσκουν τρόπο να βελτιώσουν τον ήχο

Der Bosonen-Blues - Teilchenphysiker helfen alte

Tonaufnahmen von Schellackplatten und Wachszy lindern zu retten

Physicists find method to improve audio

Laser pour vieux vinyles

LISTENING TO RECORDS BY LOOKING AT THEM

Aus alt mach neu

Fizycy ratują stare winyle

Playing Old Records (No Needle Required)

New Hope For Old Sounds

Optical Metrology Reconstructs Audio Recordings

Digitizing the voices of the past

Science perfects sound of century-old recordings

Virtual Record Player Preserves Historic Recordings

Particle Tracking Tunes Up Music

Physicists Seek to Digitize Music, Restore Media

Groovy Pictures: Extracting sound from images of old audio recordings

How to listen to old records in the 21st century

Rescuing Recordings

REAL LIFE NEWS: PRESERVING ANCIENT RECORDINGS

Técnica permite recuperar LPs danificados pelo tempo

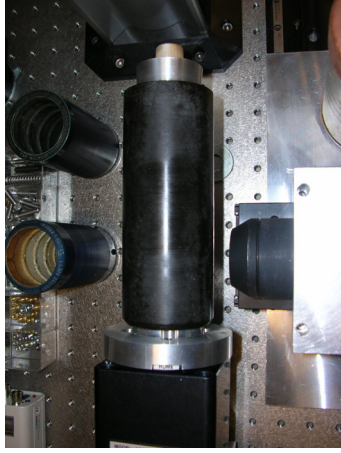
Inspirado na física de partículas, método digitaliza gravações sem riscos e chiados

Why I read Physics Today

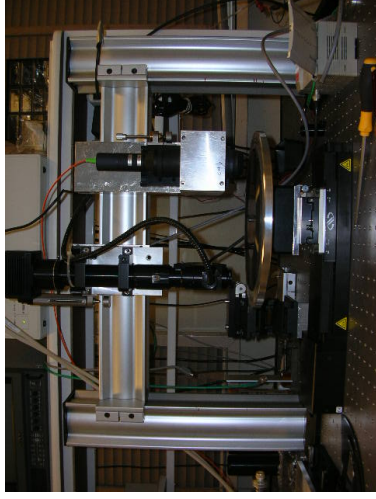
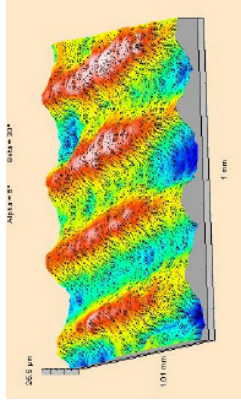
Links to Preservation and Access

- LBNL research
 - www-cdf.lbl.gov/~av
- National Endowment for the Humanities
 - <http://www.neh.gov/grants/guidelines/researchdevelopment.html#howto>
- The Library of Congress
 - <http://www.loc.gov/rr/record/nrpb/> (National Recorded Sound Preservation Bd.)
 - <http://www.loc.gov/rr/record/> (Recorded Sound Division)
- The Council on Library and Information Resources
 - <http://www.clir.org/>
- The Audacity software project (free sound editing software)
 - <http://audacity.sourceforge.net/>
- The Edison National Historic Site
 - <http://www.nps.gov/edis/home.htm>
- Sound recording history
 - <http://www.recording-history.org/index.htm>

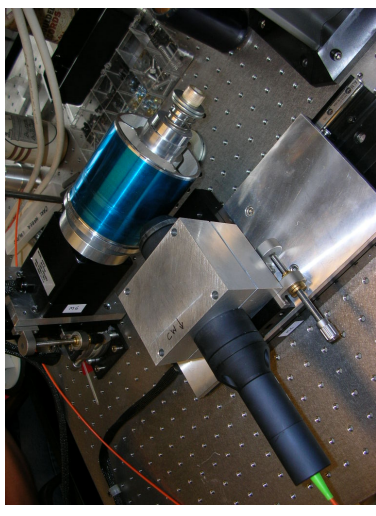
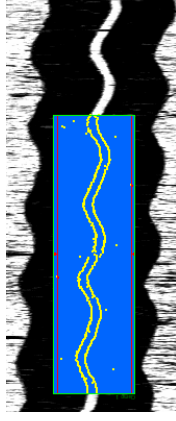
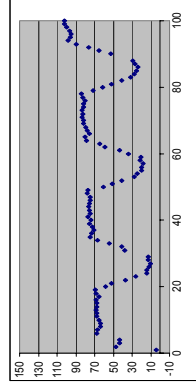
Optical Scanning: A general tool to preserve and create access to recorded sound history



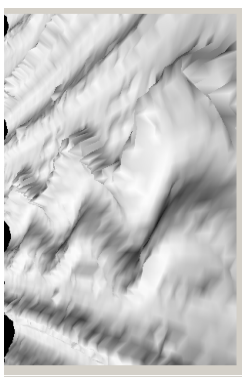
Wax cylinder



Shellac disc



Plastic dictation belt



• Web site URL: www-cdf.lbl.gov/~av