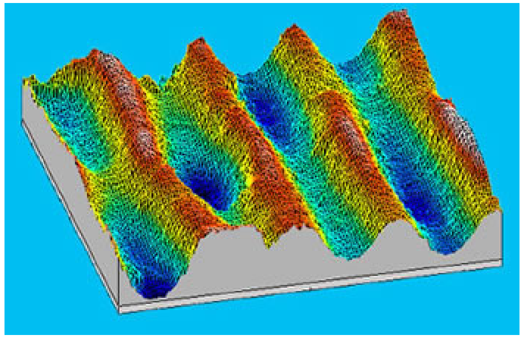
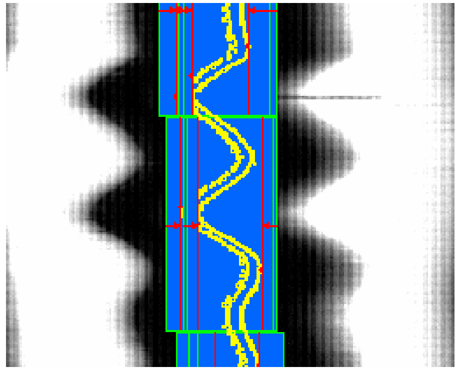




Using Optical Metrology to Restore Sound Recordings

Collaboration and Support

Lawrence Berkeley National Lab
The Library of Congress
University of Southampton, U.K
EIF Fribourg

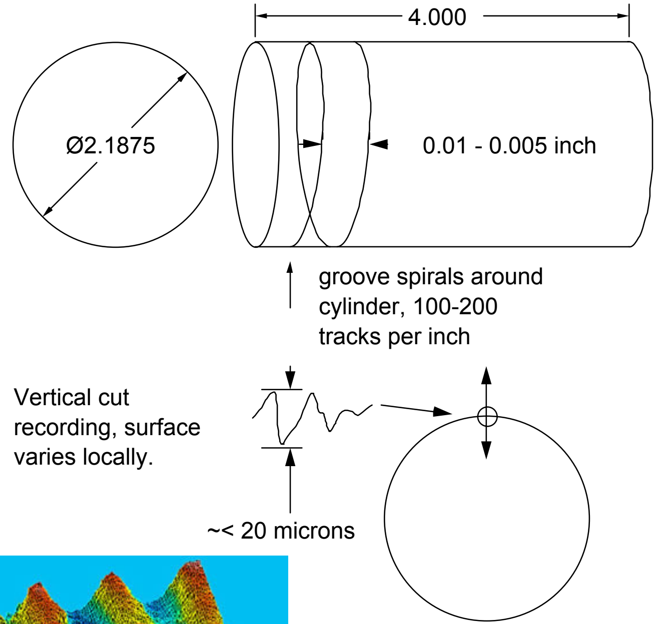
Financial Support from the
Library of Congress,
National Endowment for the Humanities,
A.P. Mellon Foundation,
National Archives
J.S. Guggenheim Memorial Foundation,
DOE

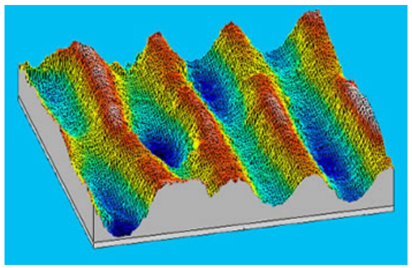
Outline

- 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.
  - **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…, "
- We study methods inspired by HEP detector instrumentation, and analysis, to recover sound recordings.
- A good illustration of how the approach of the physical sciences can benefit other fields of study.

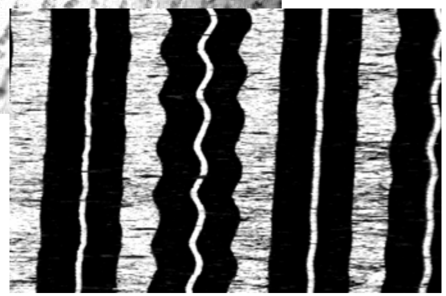
Mechanical Recording Principles

Cylinder: groove varies in depth (Vertical Cut)



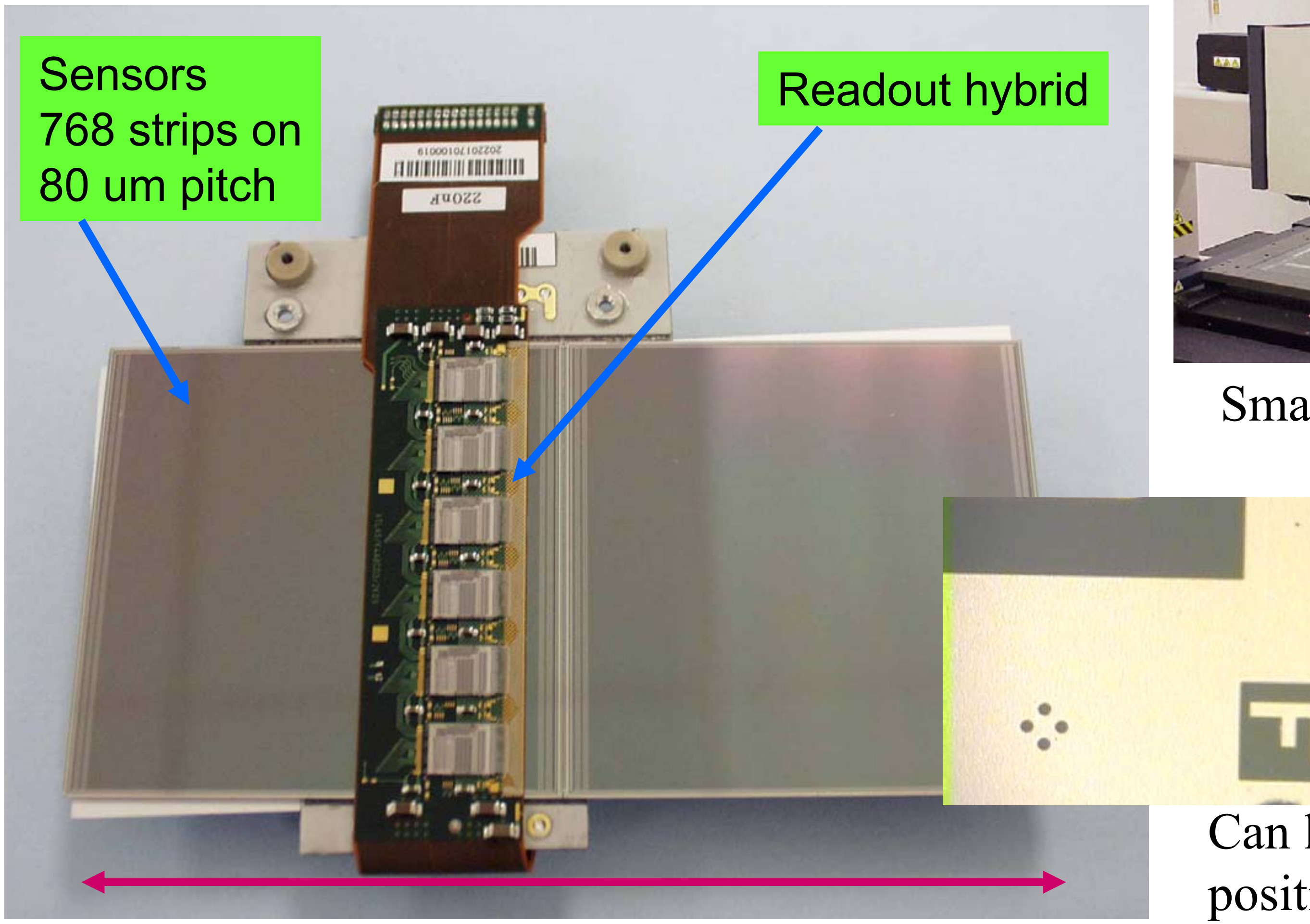


Disc: groove moves from side to side (Lateral Cut)

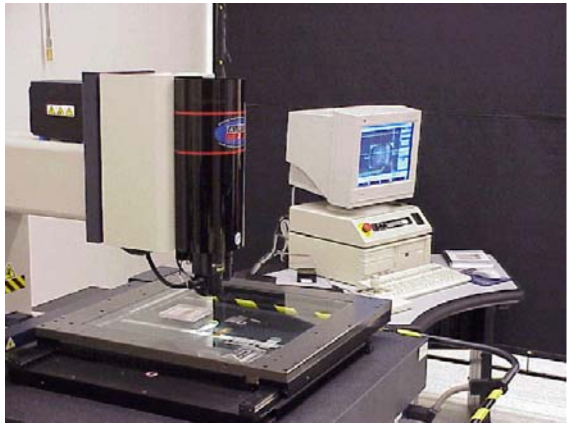


Audio is encoded in micron scale features which are >100 meters long

Optical Metrology of ATLAS Modules



12 cm



SmartScope

Corner fiducial mark

Can locate detector position with ~micron precision

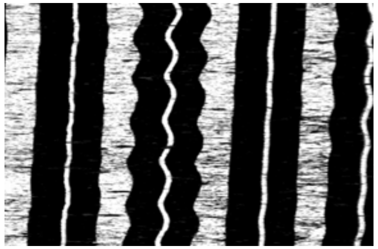
Archives and collections now transfer recordings to more stable and accessible formats using modern stylus players and conservation protocols. Requires contact to the media, and audio professionals.

Here instead use optical metrology and image processing to create a digital representation of the complete record surface, and then “play” it with a virtual needle. This is a very general approach and no contact to the record is required.

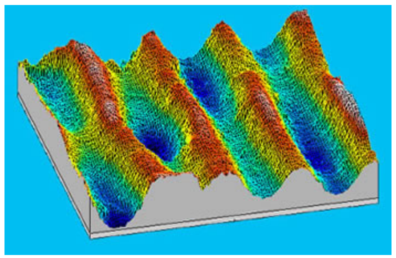
Non-Contact Digital Imaging

- 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

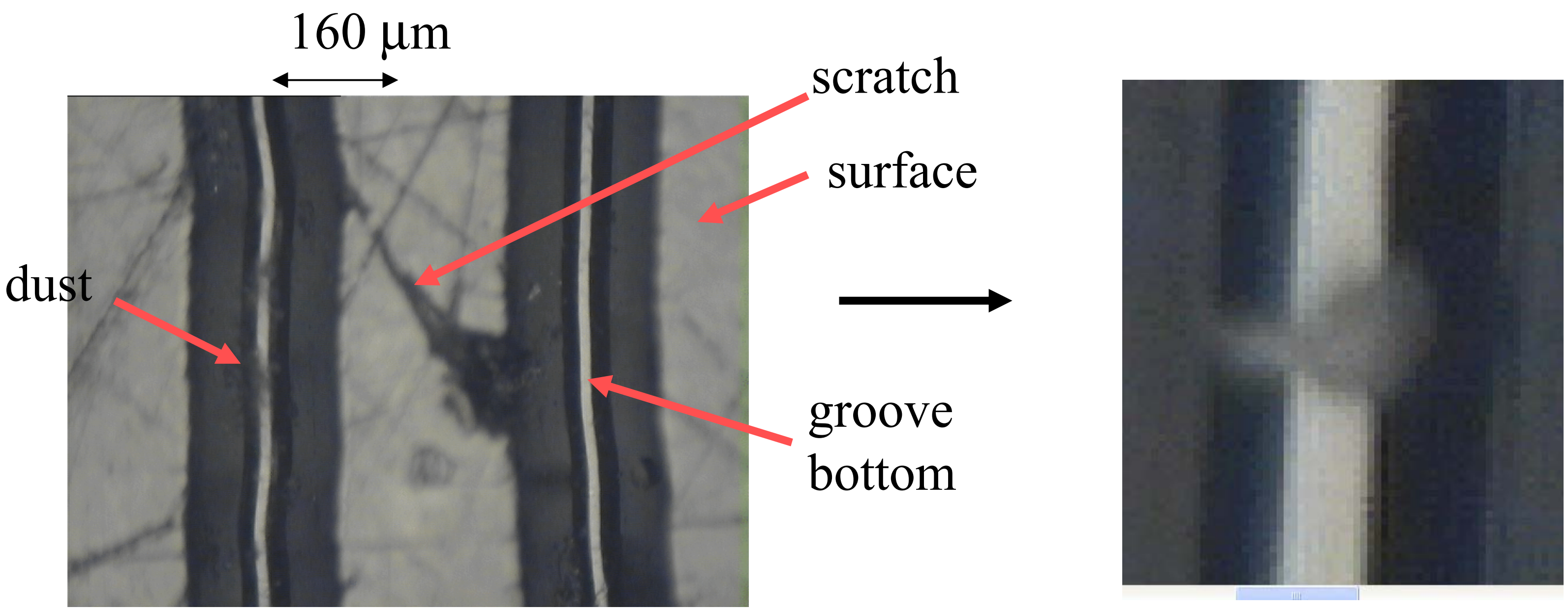


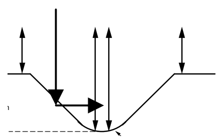
Micro-photograph of shellac disc:
A two dimensional image “2D”
can measure lateral grooves



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

2D Imaging: Electronic Camera



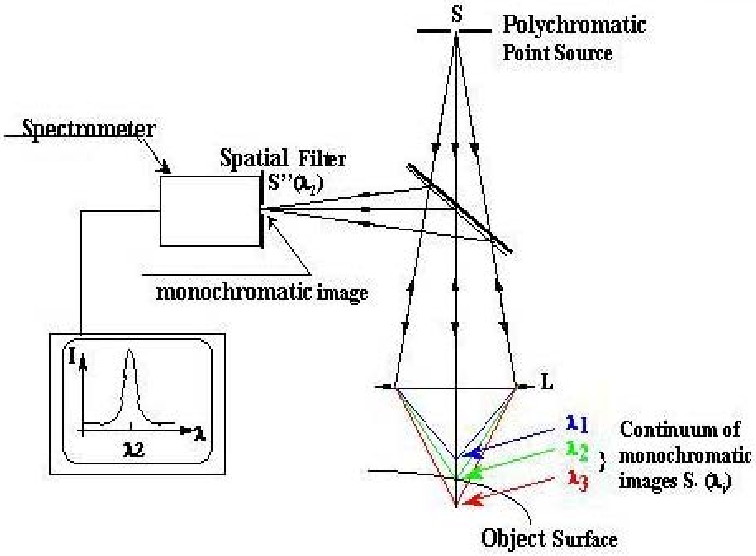


- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface
- High speed cameras allow near "real-time" imaging

3D Imaging: Confocal Scanning Probe

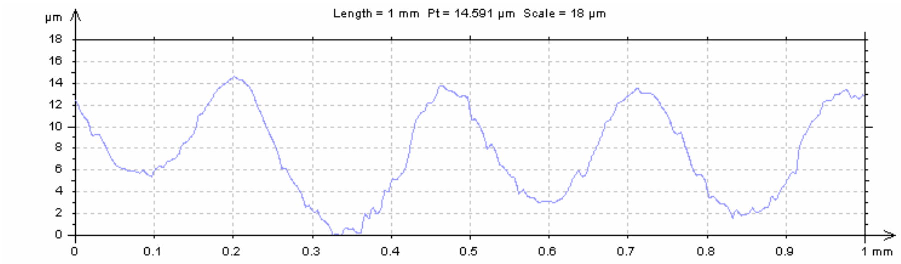
Required for cylinder with vertical groove modulation.

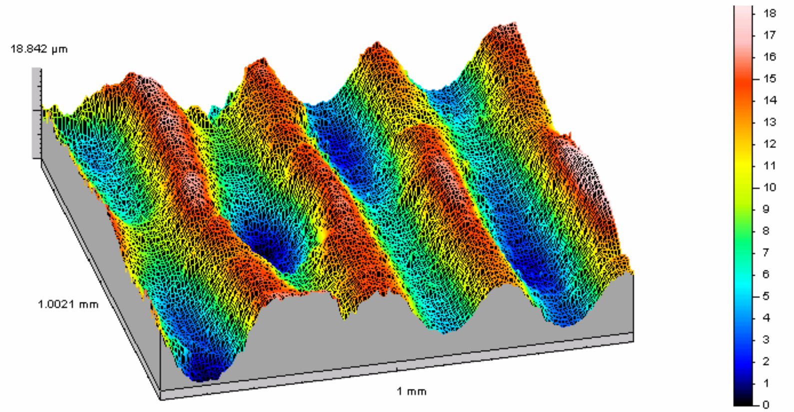
Point by point scan
0.01 degree = 96 KHz



Up to 4000 pts/second

Surface of an Edison cylinder



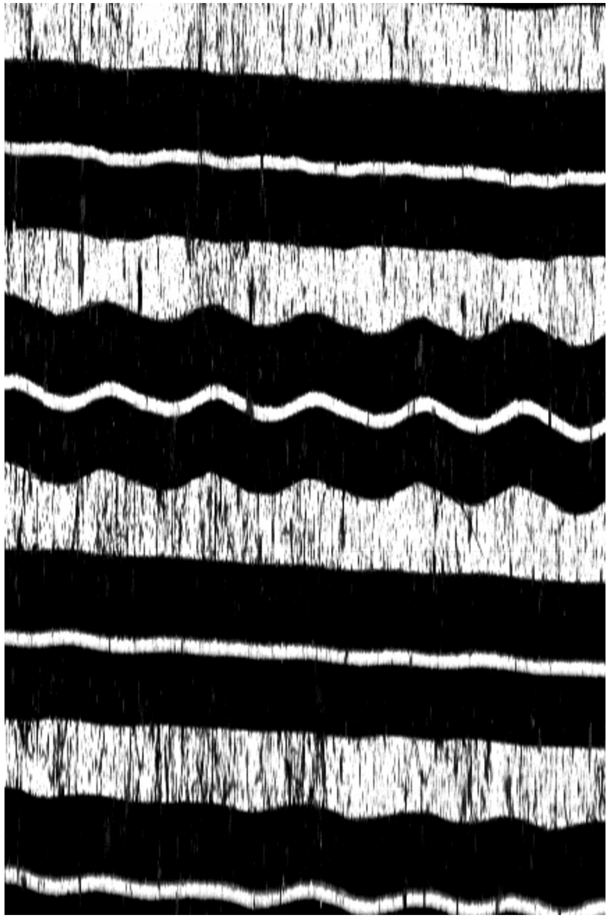


To cover the entire surface of a record requires many hours of scan time, depends upon grid used

Pixelized image determines sampling

Time

Amplitude

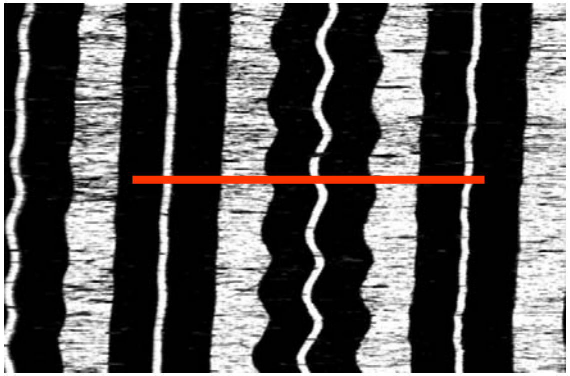


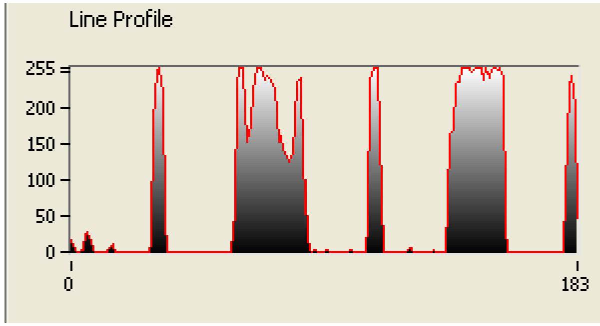
Natural segmentation by pixel size, magnification, resolution

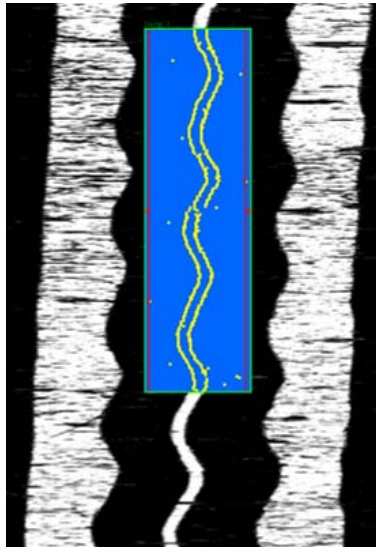
Easily time sample to >300 KHz

Amplitude sampling set by resolution
~0.3 microns / 250 microns max

Image Analysis (2D case)

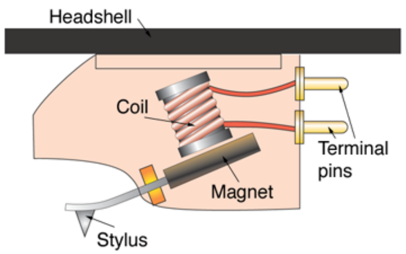






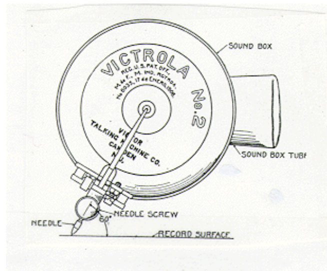
What is the relationship between “groove” and sound?

Electro-magnetic case

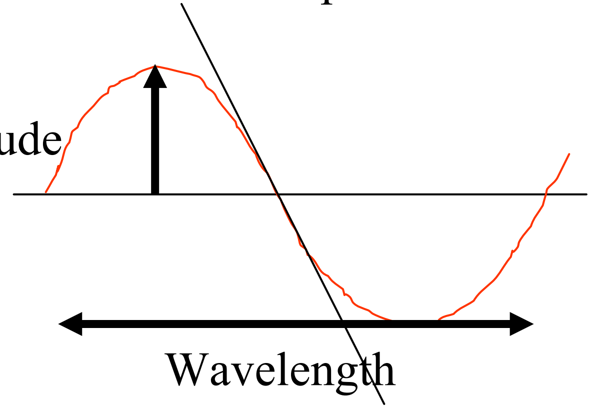


induction

Acoustic case



Diaphragm is over-damped to provide flat response



Sound = Stylus Velocity

(“constant velocity condition”)

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

Comparison

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

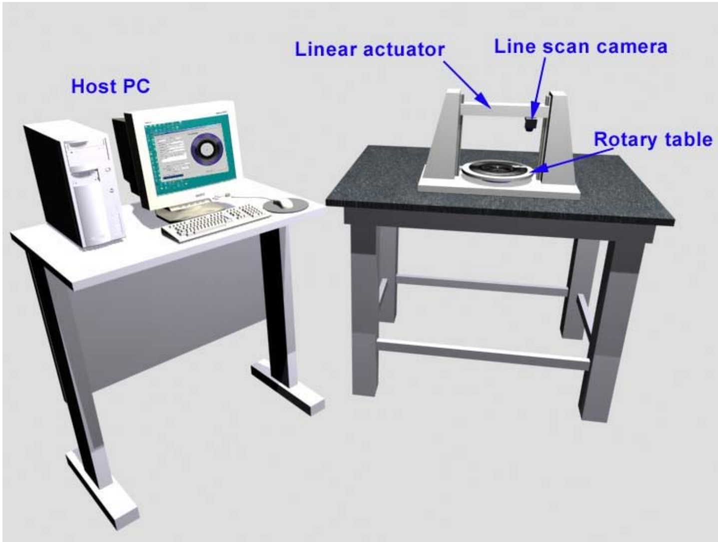
- ♪ Non-contact
- ♪ Robust – wax, metal, shellac, acetates…
- ♪ Effects of damage and debris reduced by image processing
- ♪ Re-assemble broken media
- ♪ Resolve noise in the "spatial domain" where it originates.
- ♪ Use of groove geometry.
- ♪ Effects of skips are reduced.
- ♪ Distortions (wow, flutter,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

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
  - 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

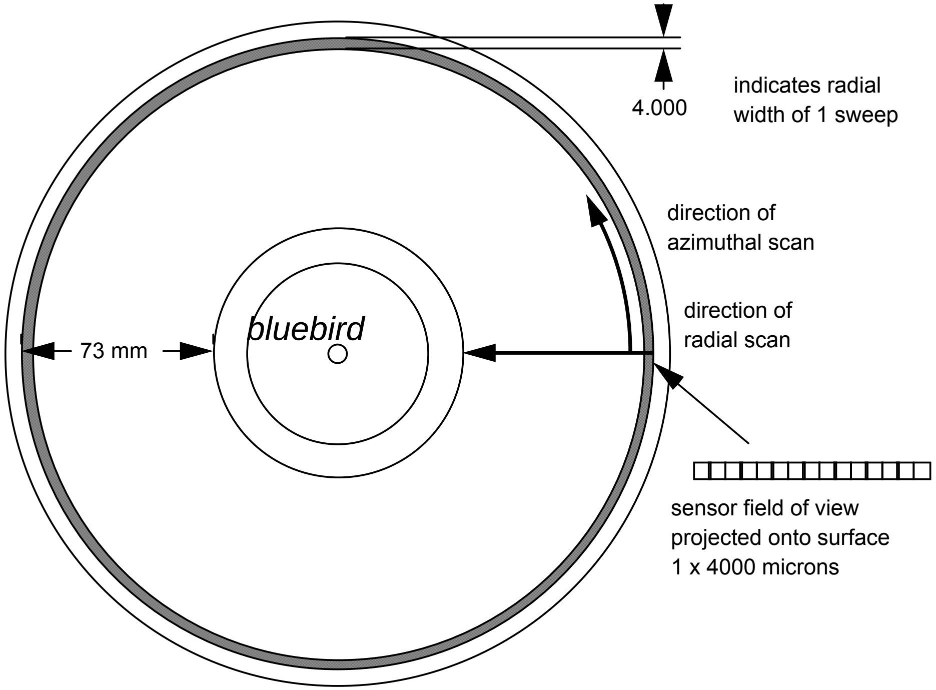
I.R.E.N.E.

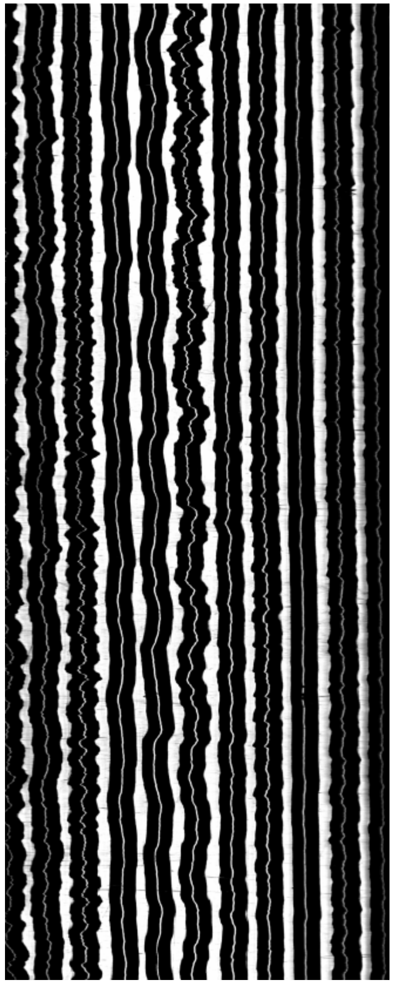
Image, **R**econstruct, **E**rase **N**oise, **E**tc

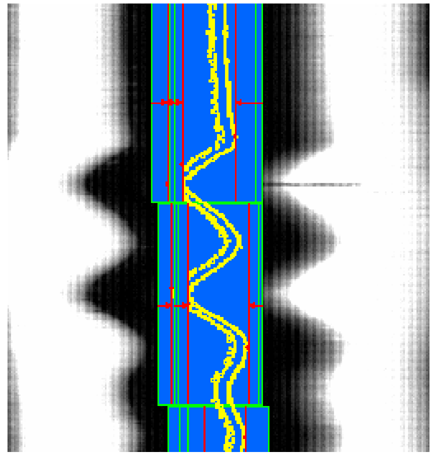


- Under evaluation at the Library of Congress
- Scan time 5-15 minutes for a 3 minute disc
- User friendly interface
- Emphasize throughput and diversity (access)
- Provide statistical measures of media condition
- Production-like machine and test-bed for future development

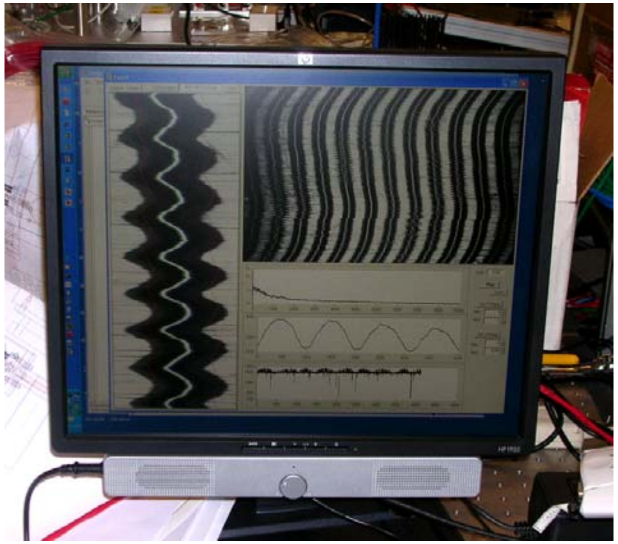
Line Scanning: disc is in motion

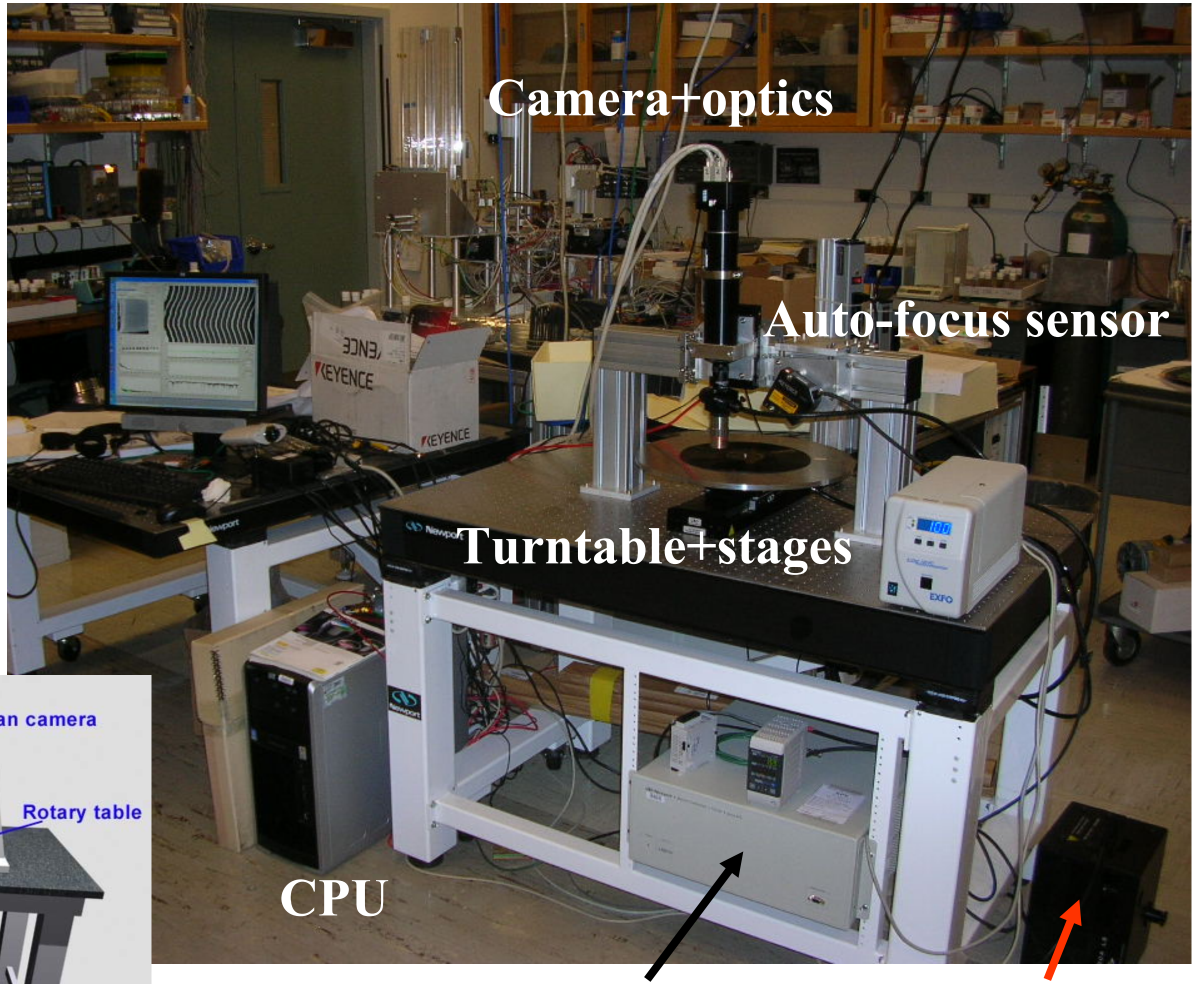


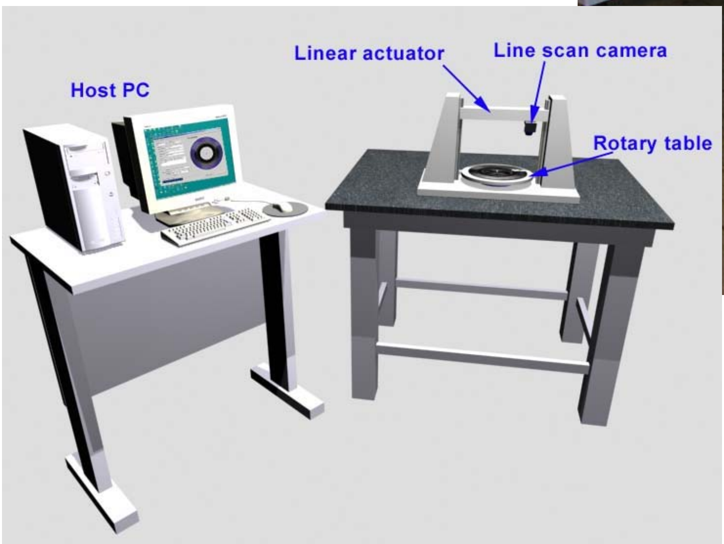


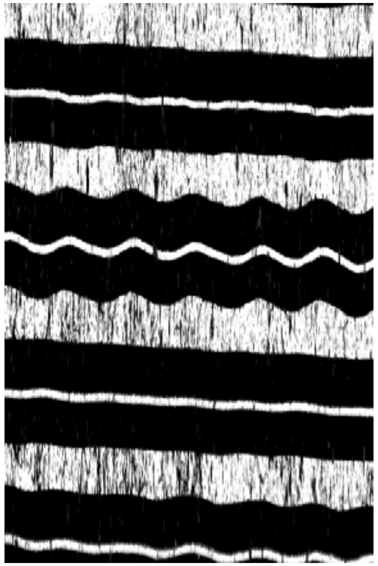


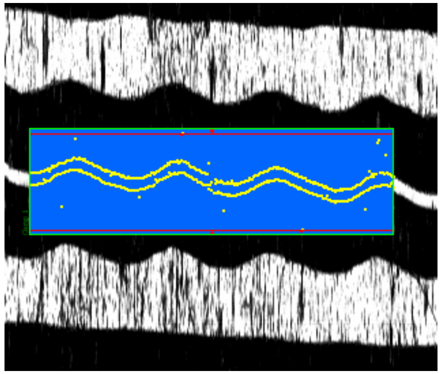
- 6000 pixels@15 K lines/s
- 7.6 x 10^5 lines/outer ring
  - **390 KHz max sampling**
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.



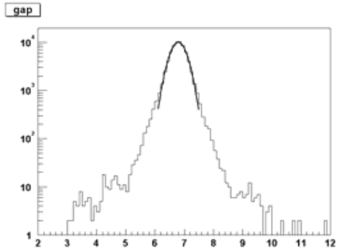

Camera+optics
Auto-focus sensor
Turntable+stages
CPU
Motion control
Light source


Linear actuator
Line scan camera
Host PC
Rotary table

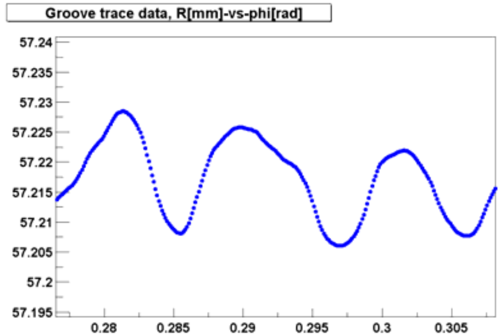




ΔR distribution



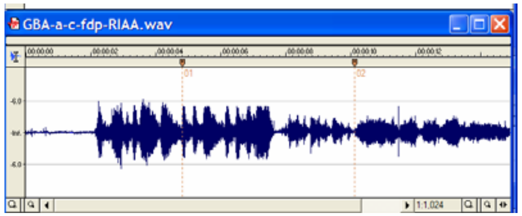
Width across groove bottom

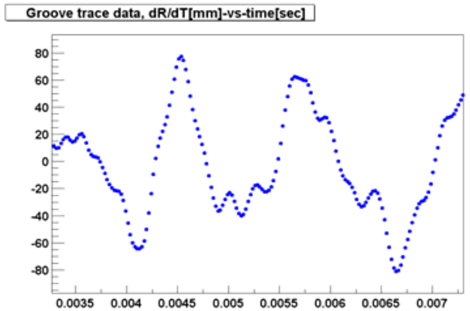


Average
Filter using ΔR<cut

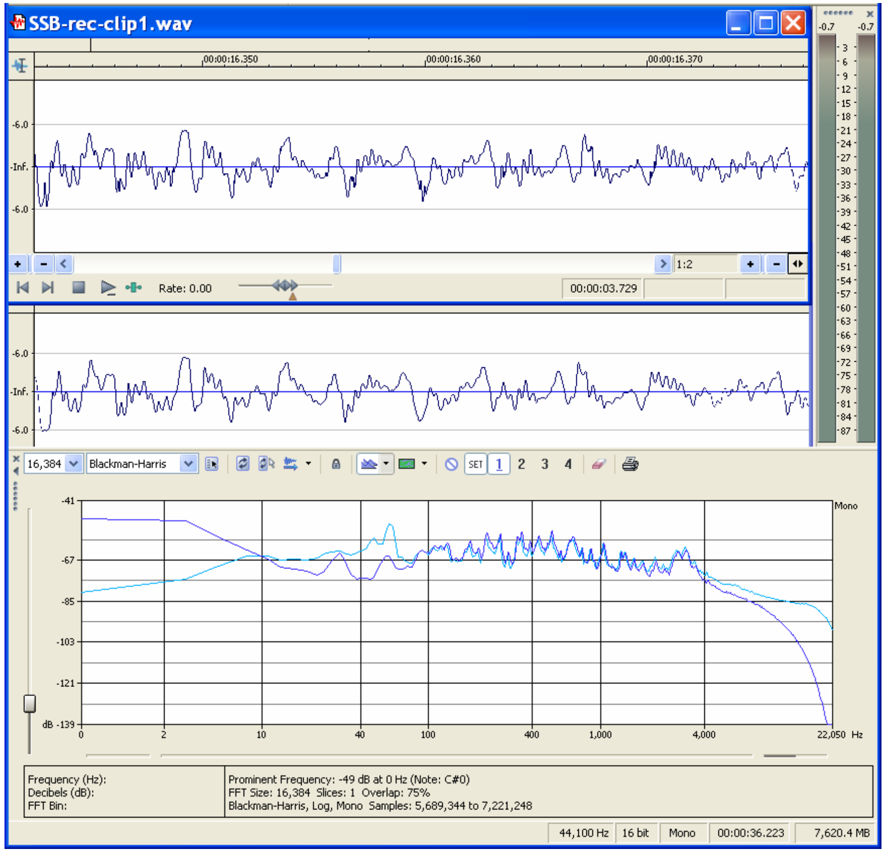
Time
Pixels = 104 KHz

Measure slope
at each point
(stylus velocity)





The Star Spangled Banner: Kate Smith

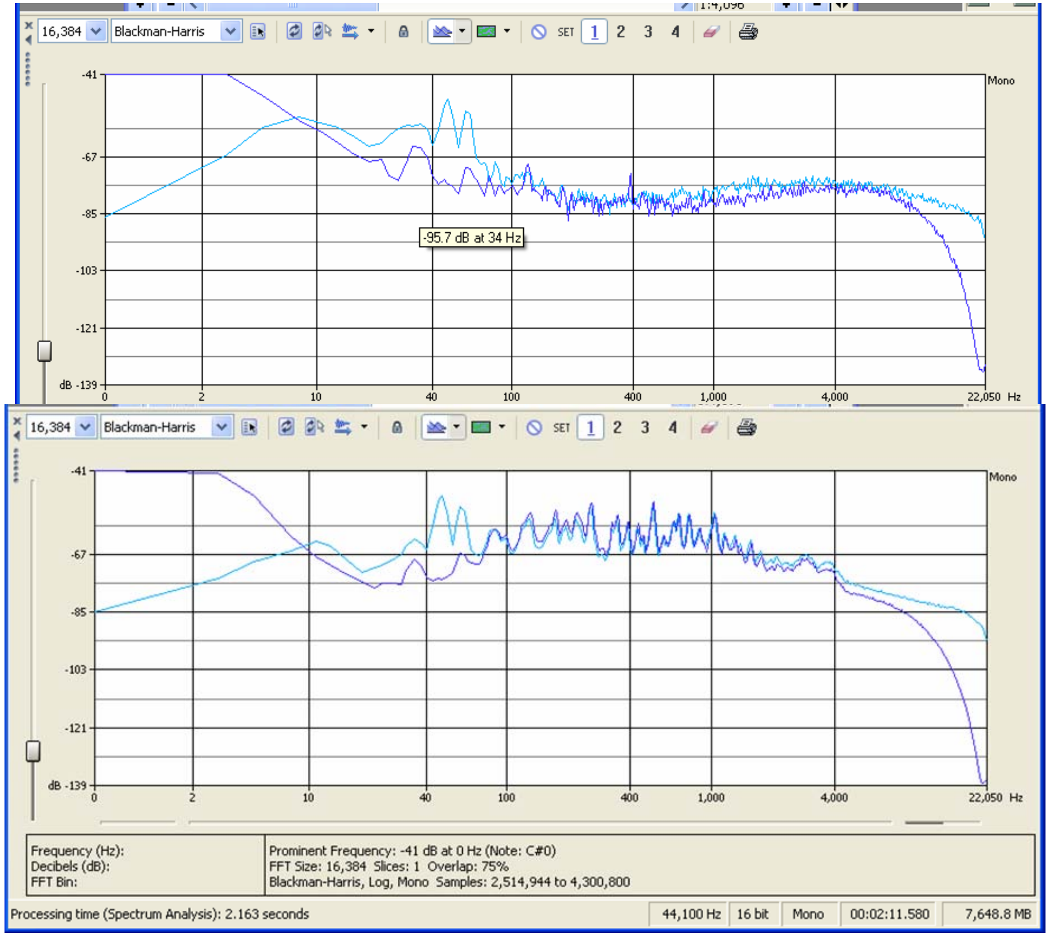


stylus

IRENE

78 rpm shellac disc with moderate wear,
RIAA curve applied

Goodnight Irene: Weavers 1950



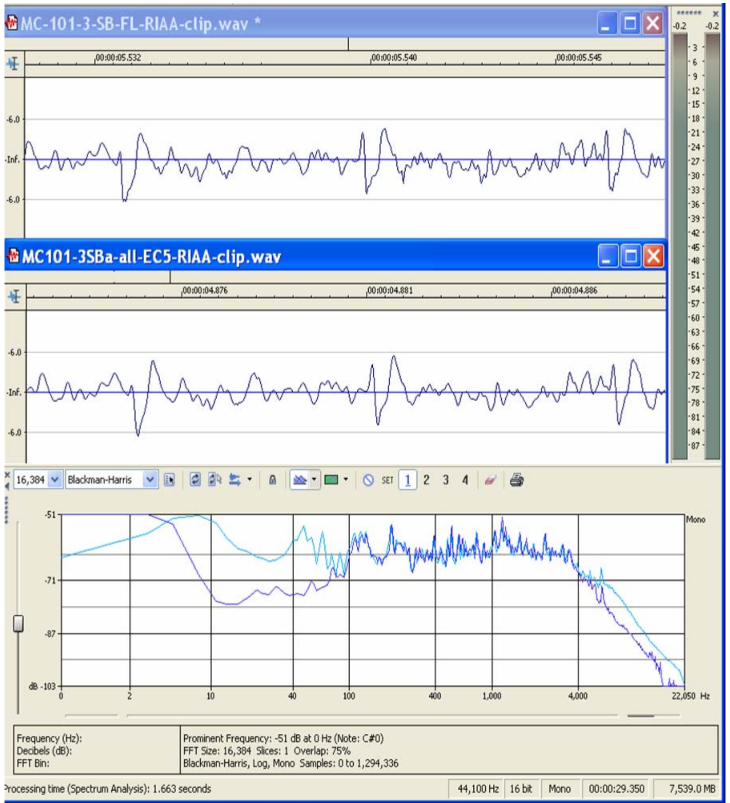
Noise spectra

record

IRENE

Studio Test 1947

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

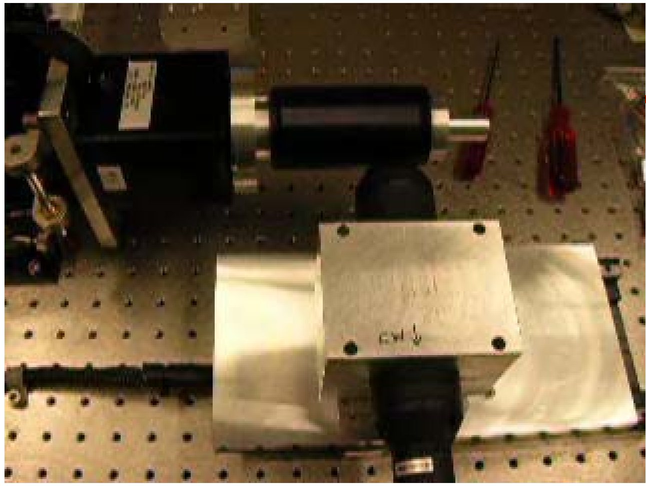


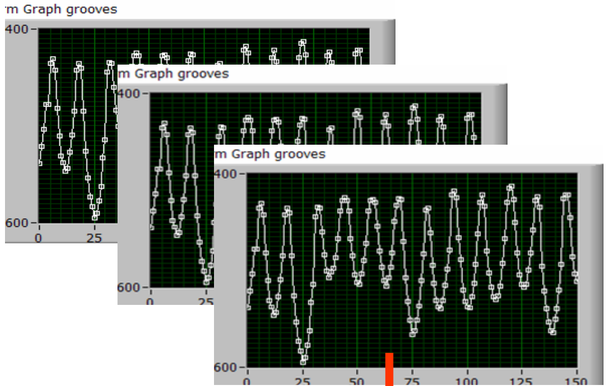
stylus

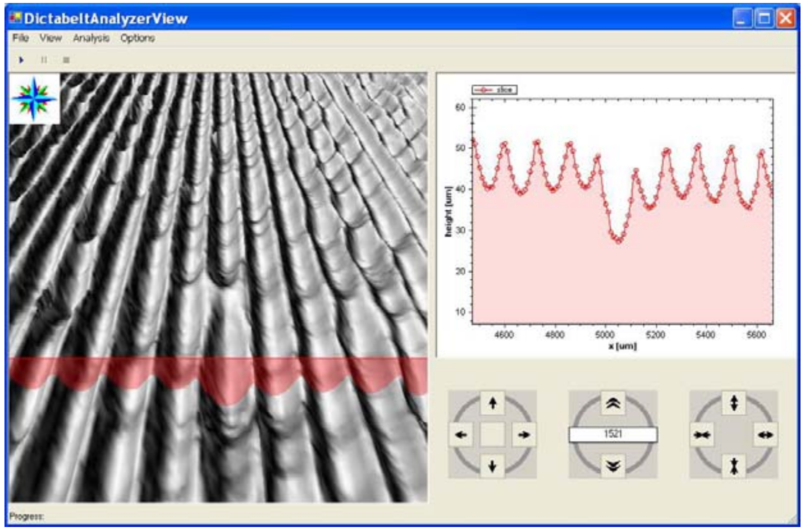
IRENE

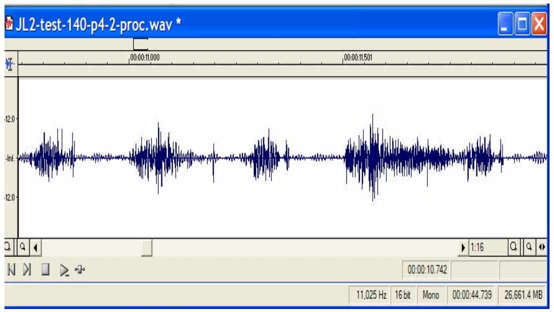
Lacquer disc, RIAA EQ

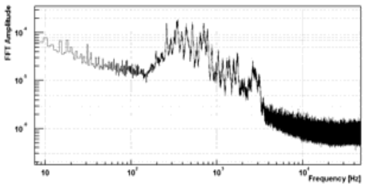
Cylinder Scanning



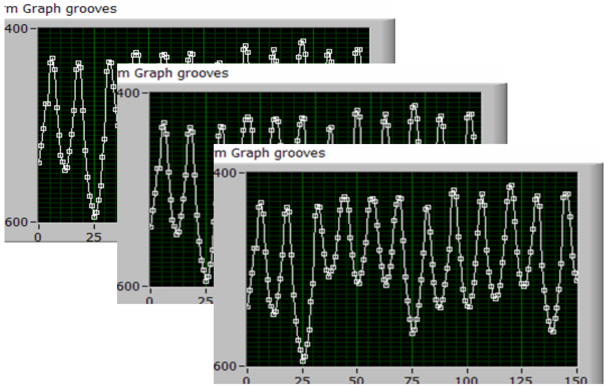




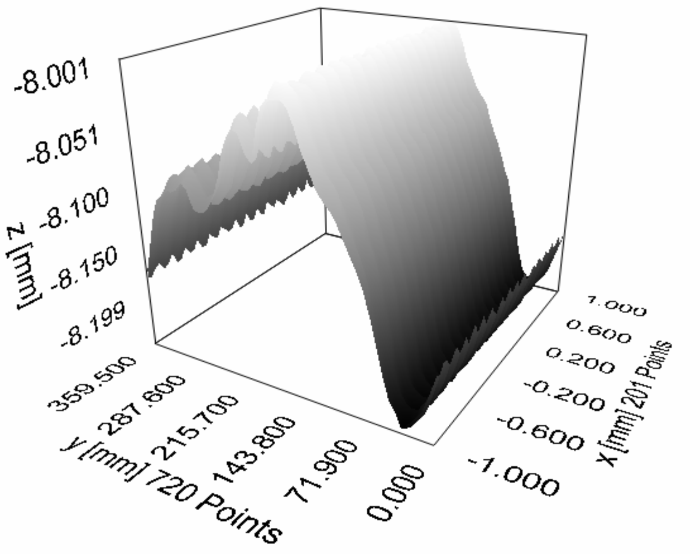




Sample at 96KHz to minimize effect of aliasing



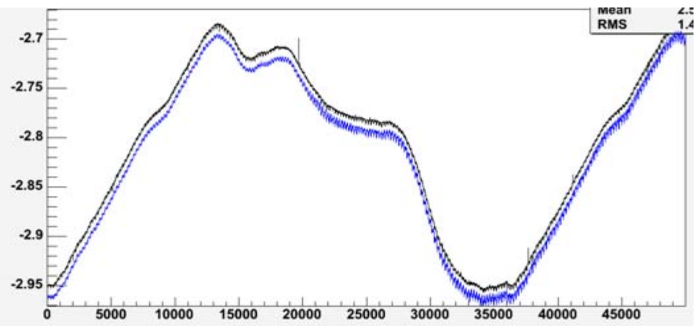
Sequential axial scans



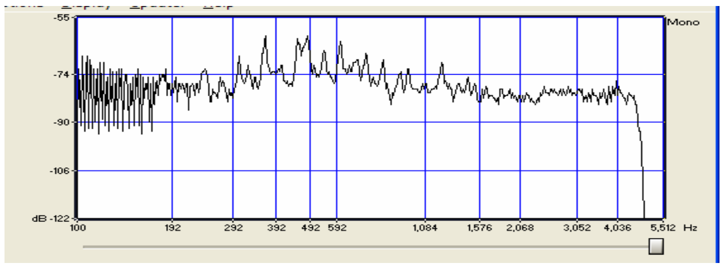
Subtract valleys from ridges to correct for overall shape

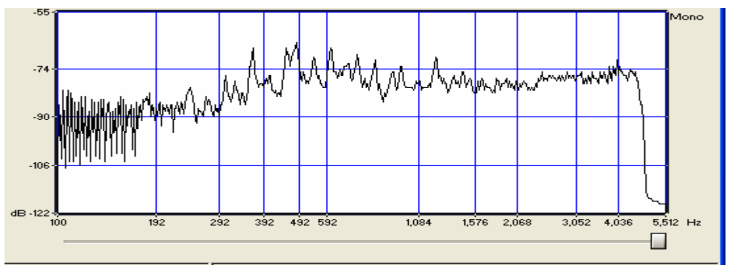
(Ridges provide (approx), geometrical reference)

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

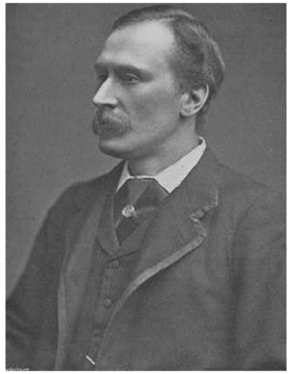


d/dt





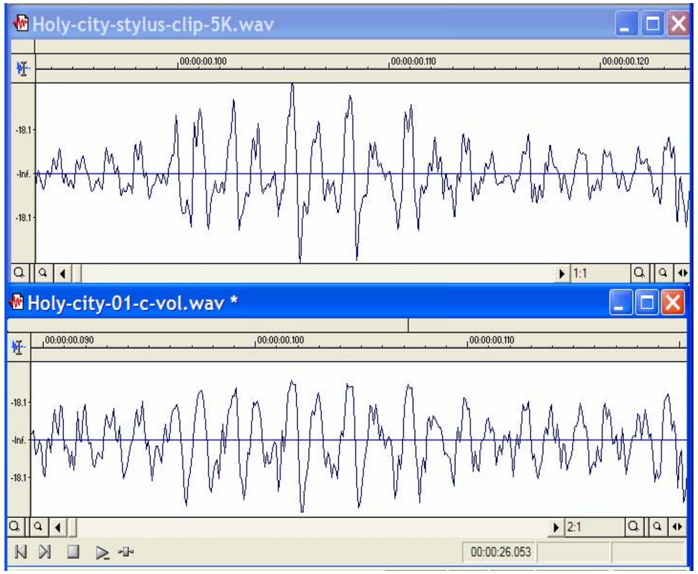
Sound Comparison

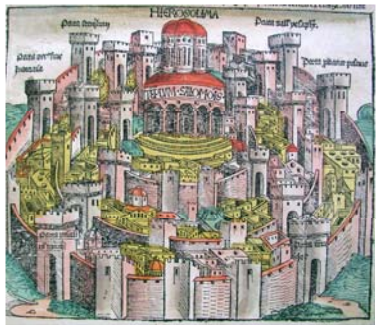


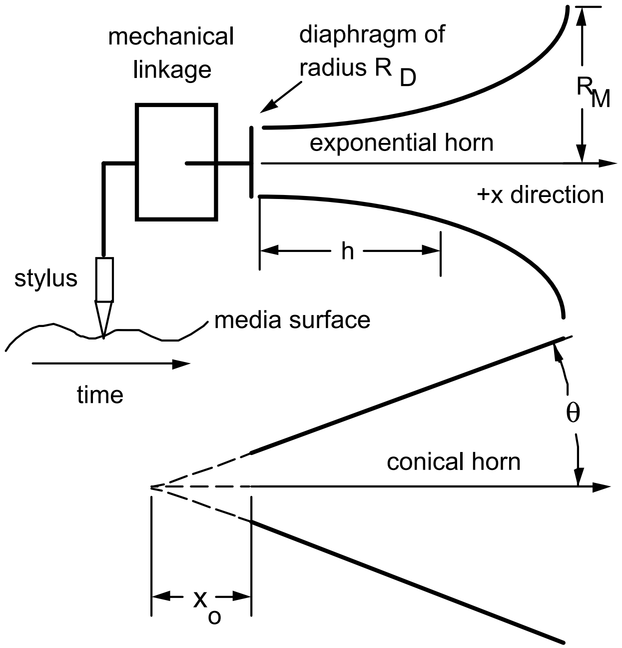
- The Holy City, composed by Stephen Adams,

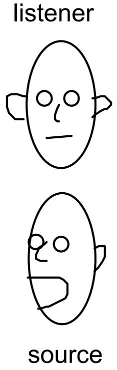
The Edison and Skedden Mixed Quartet, Amberol 1601

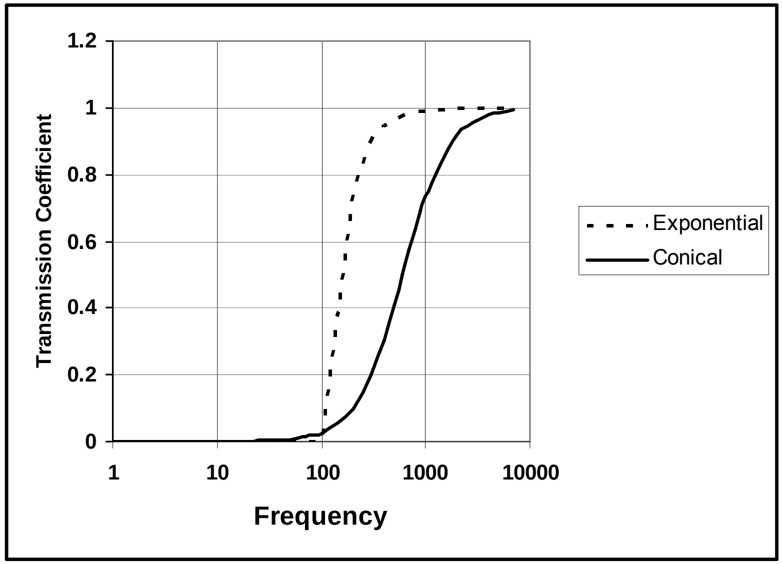
- Stylus
- Optical
- Optical + filter + EQ







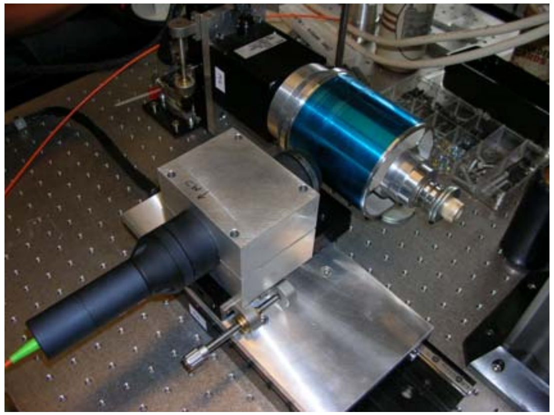


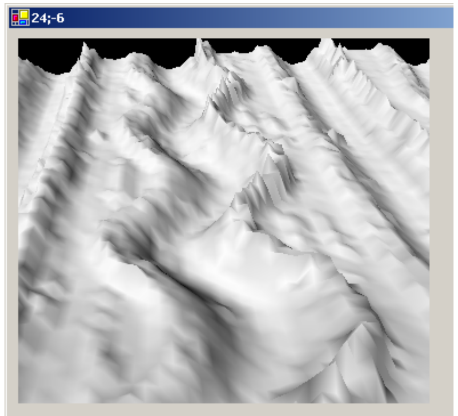


Response of horn and diaphragm at low frequency can modify response and deviations from "constant velocity" characteristic.

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



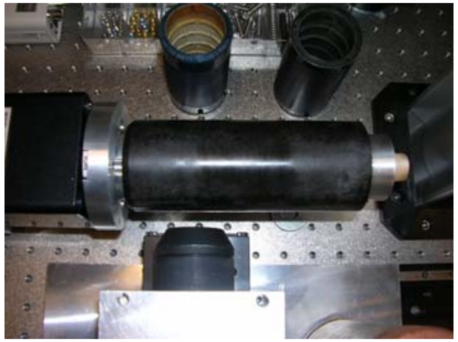


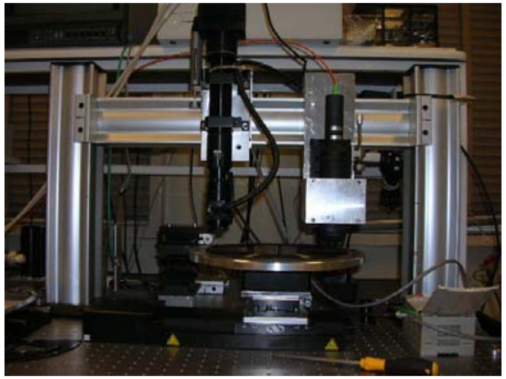
From Top Quarks to the Blues
Particle Tracks Tune Up Music
Physicists Seek to Digitize Music, Restore Media
Using high-energy physics to preserve old records
Scientists find new way to play old records
Optical Metrology Reconstructs Audio Recordings
From the Higgs Boson Particle to Leadbelly
Teilchenphysik 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 Wachszylindern zu retten

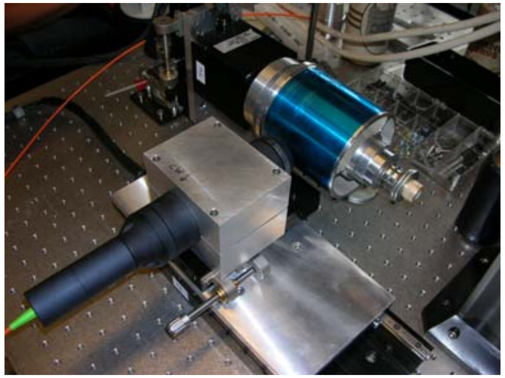
Physicists find method to improve audio
Laser pour vieux vinyles
LISTENING TO RECORDS BY LOOKING AT THEM
Aus alt mach neu
Fizycy ratują stare winyle
Playing Old Records (No Needle Required)
New Hope For Old Sounds
Optical Metrology Reconstructs Audio Recordings
Digitizing the voices of the past
Science 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

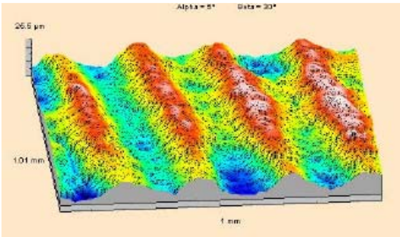
Why I read Physics Today

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

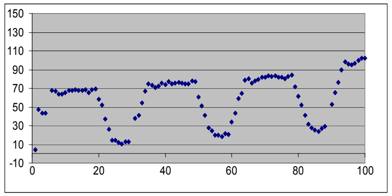


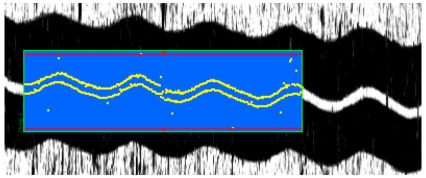






Wax cylinder





Shellac disc

Plastic dictation belt

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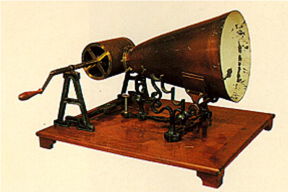
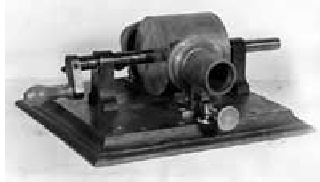
Web site URL: www-cdf.lbl.gov/~av



History



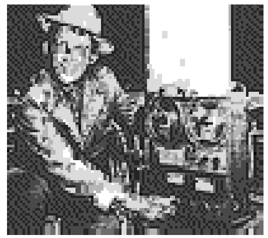
- 1859 Leon Scott invents *Phonoautograph* paper recorder
- 1877 Thomas Edison invents sound reproduction on tin foil *Phonograph*

Discos fonográficos Pathé
Caras y Caretas (7/7/1906)

- 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



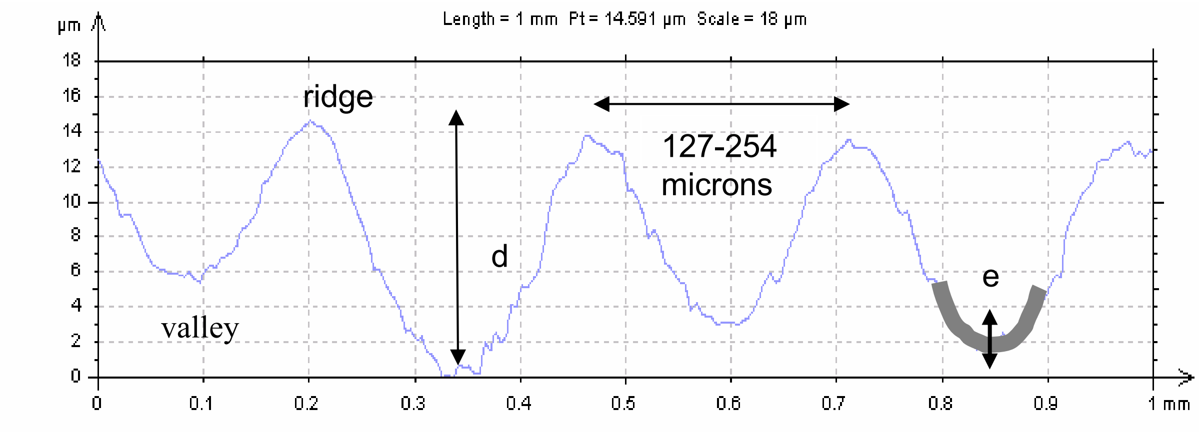
- 1947 Magnetic tape in production use, Ampex 200A
- 1948 33 1/3 rpm LP introduced
- 1958 Stereophonic LP on sale, uses 45/45 system

- 1963 Cassette magnetic tapes

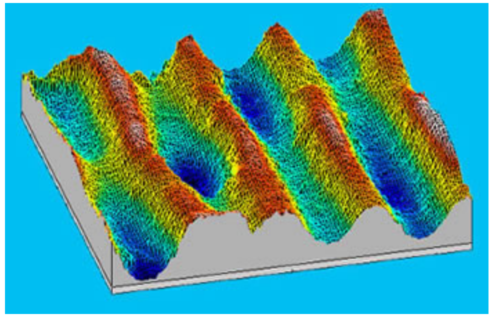
- 1982 Compact Disc (*CD*)

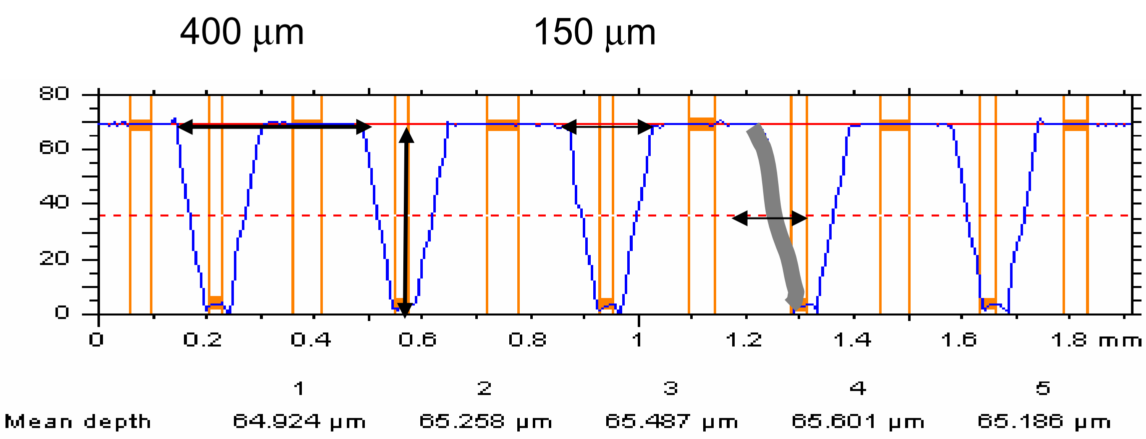
  end of the "**Analog Era**"

- 2001 Apple *IPOD*

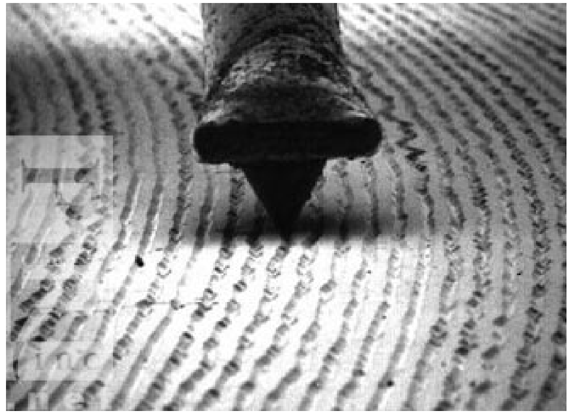


Cylinder surface





Disc surface



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

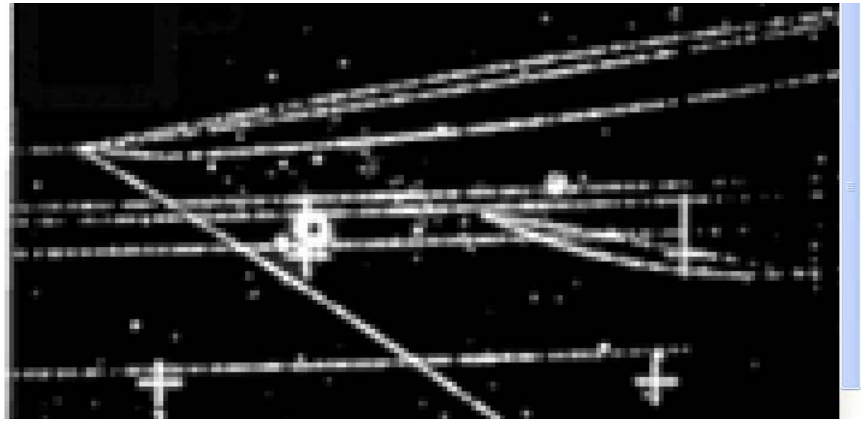
Parameter	**78 rpm, 10 inch**	**Cylinder**
Cut	Lateral	Vertical
Area containing audio data	38600 mm^2	16200 mm^2
Total length of groove	152 meters	64-128 meters
Max groove amplitude (microns)	100 - 125	~10
Groove depth (microns)	80 fixed	+/- 10 varies
Groove displacement @noise level	1.6 - 0.16 microns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

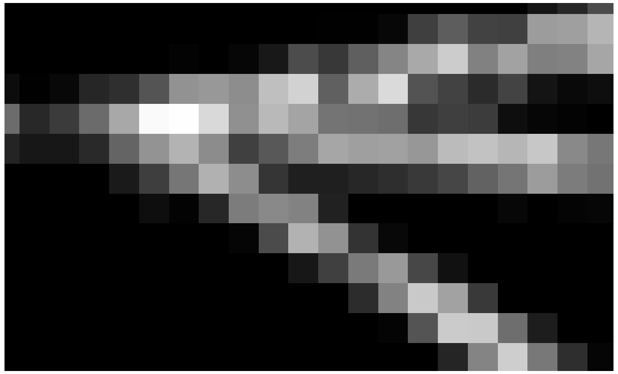
Information is encoded in sub-micron scale structures which are >100 meters long

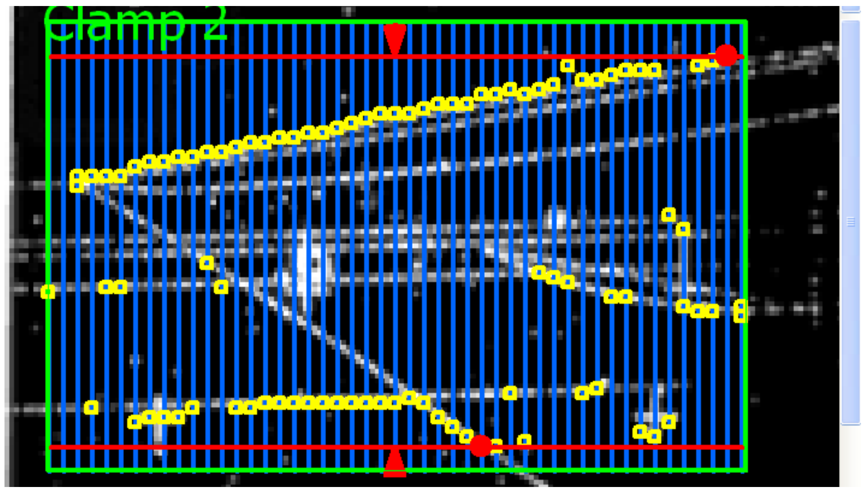
Issues for Archives

- **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

Feature Extraction from Digital Images

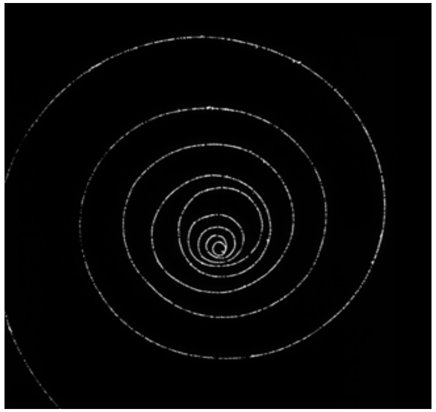






Berkeley Spiral Scanner circa 1970

Luis Alvarez
1968 Nobel Prize in Physics



"...Alvarez and his assistants have constructed a series of more and more delicate automatic scanning and measuring instruments capable of transferring the information from the photographic film into a state suitable for treatment by computer."

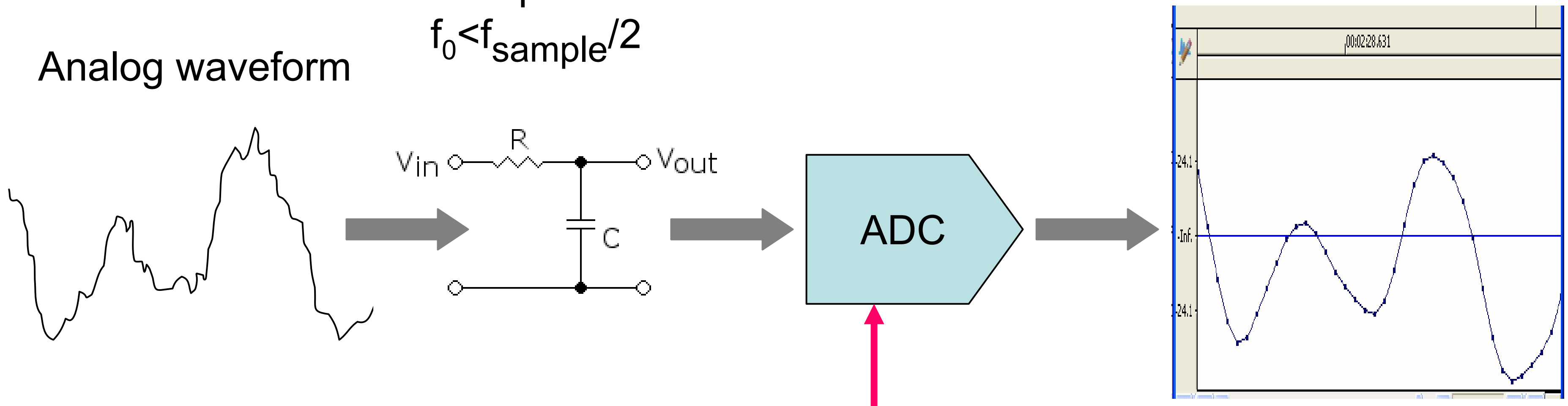
Cylinder Scans

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

Low-pass filter

$f_0 < f_{sample}/2$

Analog waveform



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

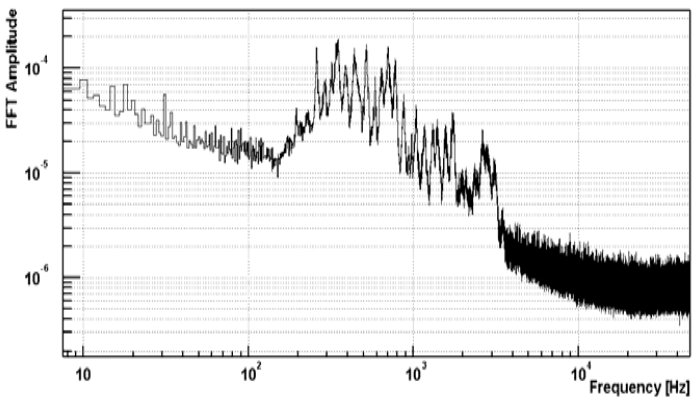
Issue of Aliasing

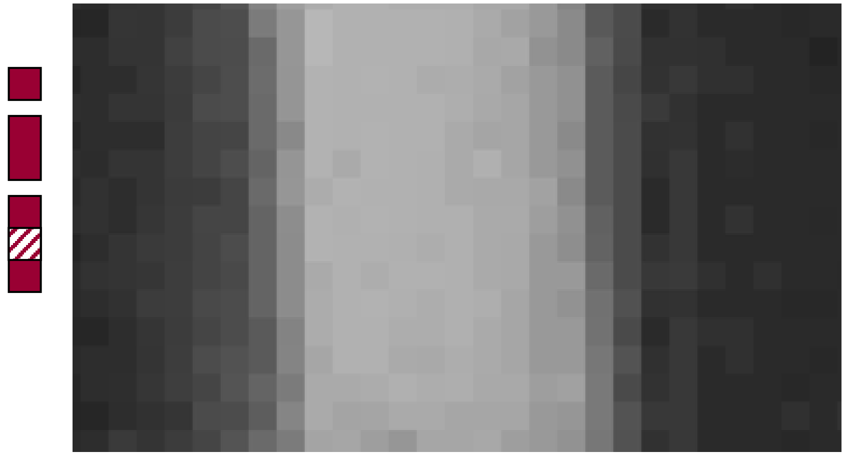
- Sampling theorem

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.

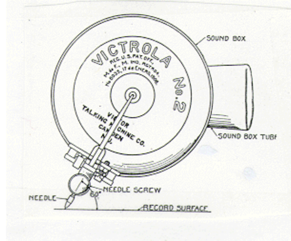
- In optical approach sampling is done by pixelization of image.

1. High sampling frequency
2. Use of pixel size to achieve effective low pass filtering?

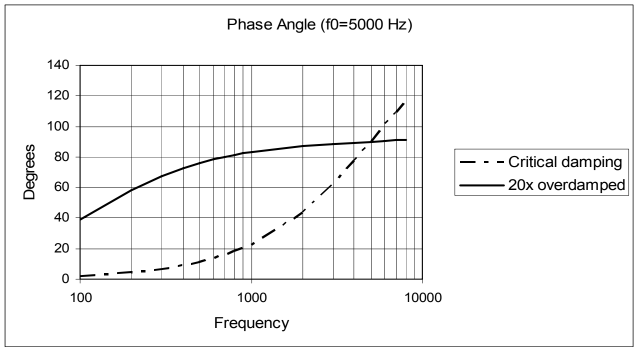




Acoustic Case



- 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

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

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

The filtering factor:

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

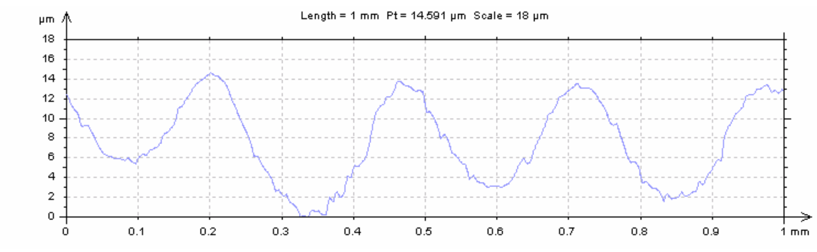
Perform the differentiation and filtering in a single processing step by:

- Doing FFT transform
- Applying *(-i k Ω) M(κ)* factor
- Doing reverse FFT transform
- Or simpler point by point methods

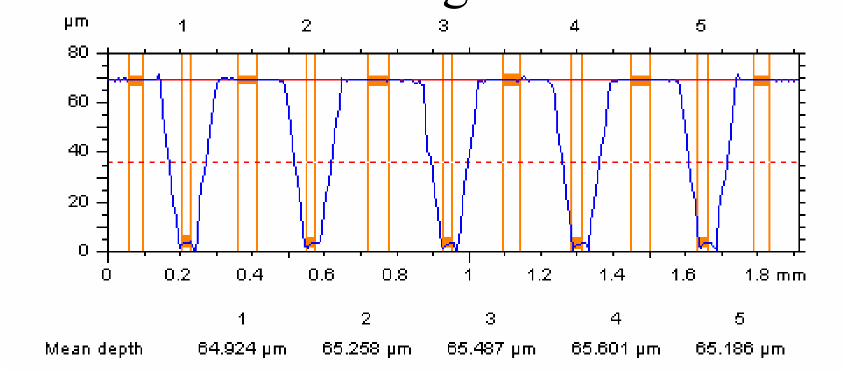
Speed and Data

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

78 rpm shellac disc

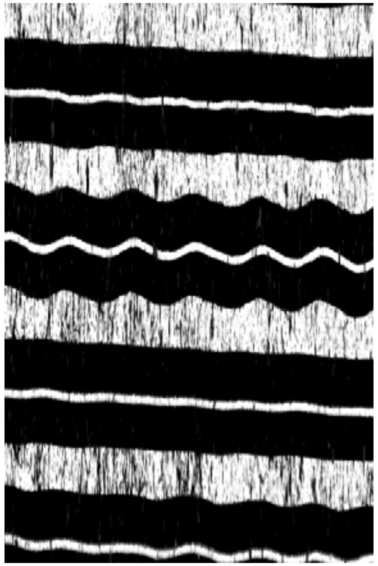
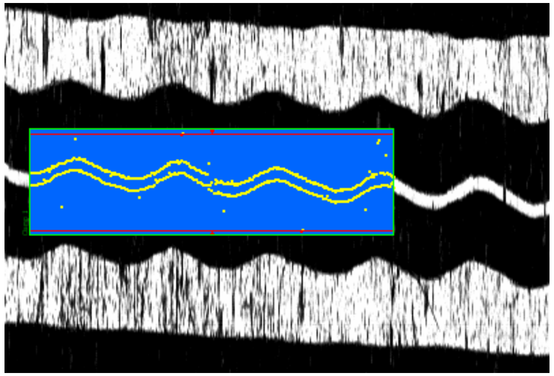
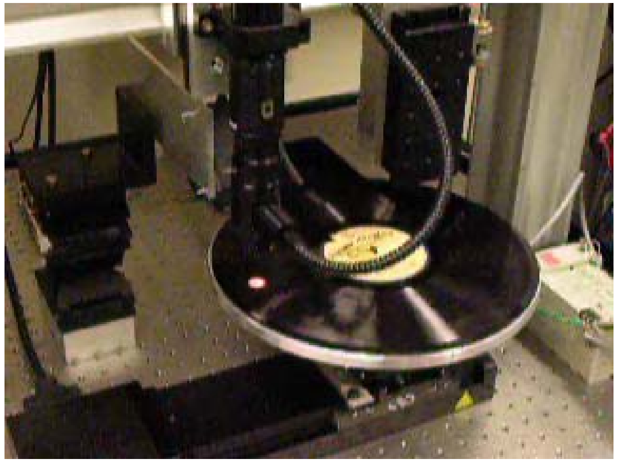


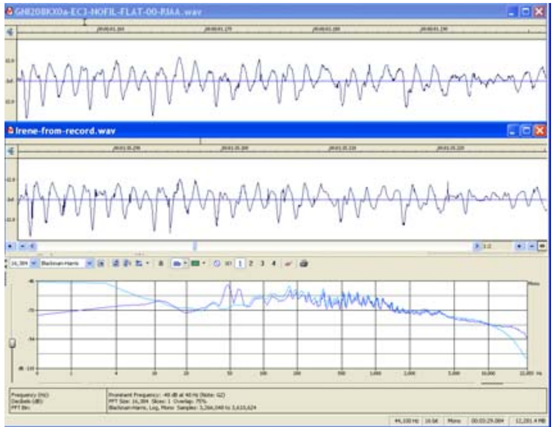
Image of groove segment

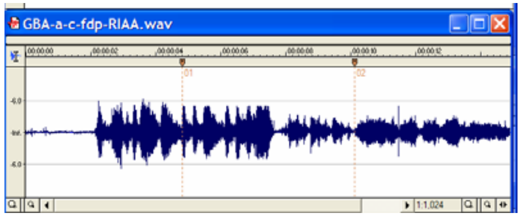


Mechanical features of groove extracted from image

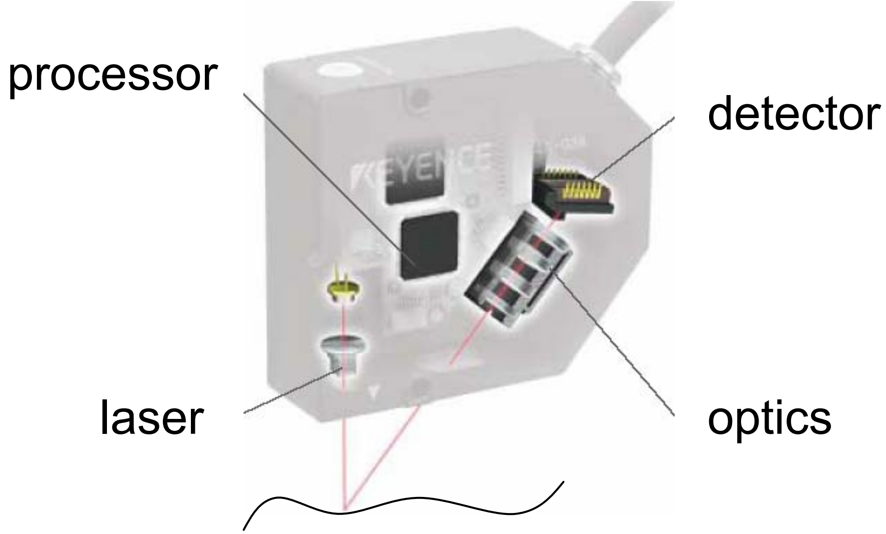


Optical line scanner: turntable with disc below, optics mounted vertically ("IRENE")

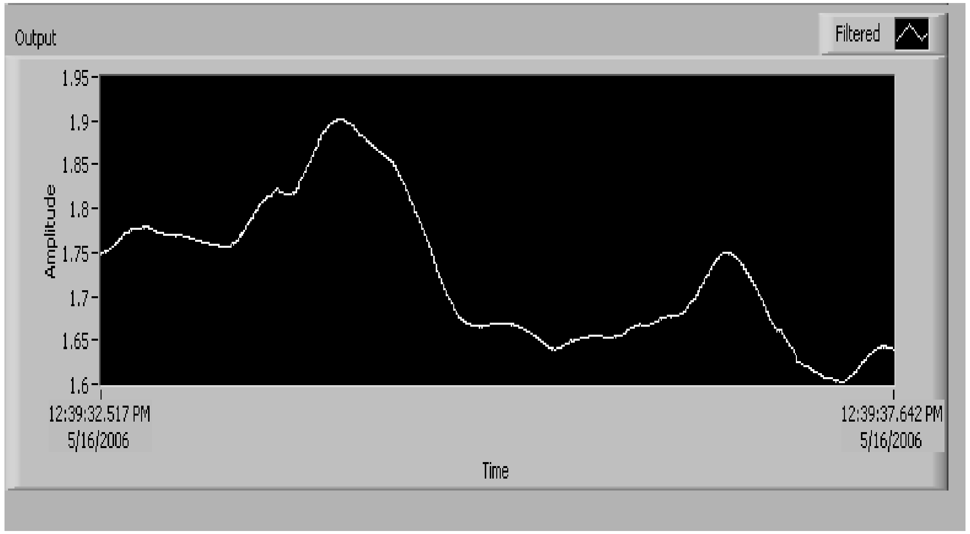




Audio waveform derived from metrology data



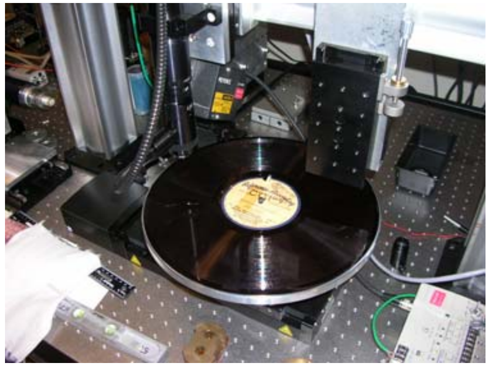
processor
detector
laser
optics



Output
Filtered
Amplitude
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
12:39:32.517 PM
5/16/2006
12:39:37.642 PM
5/16/2006
Time

Interesting Lacquer Discs

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



78 rpm acetate,
Theos Bernard,
interview, 1929

U. S. Tibetan Scholar Is Missing In Punjab After a Tribal Attack

Theos Bernard, Author, Feared Dead by Wife Who Reports Incident in New Delhi

NEW DELHI, Oct. 30 (AP)—An American student of Tibetan culture has been missing since mid-September on a trip to a Tibetan monastery and may be dead, his wife said today.

He is Theos Bernard, 40, of New York and Santa Barbara, Calif., son of G. A. Bernard of Northridge, Calif.

Interviewed here, Mrs. Bernard said shepherds had told of seeing Lahouli tribesmen attack her husband's party and kill his Moslem servants. That was in the Himalaya Mountains of northern India, she said, between Sept. 12 and Sept. 16.

Mrs. Bernard said she had learned that her husband then was short of food and she feared that he might also have lost his heavy clothing to the raiders.

Mr. Bernard set out Aug. 20 from the out-of-the-way Kulu Valley of the northern Punjab. Six days after that, she said, Hindu-Moslem rioting broke out in the valley and she herself had to flee 126 miles on foot southward to Simla. She passed through New Delhi today on her way to Calcutta, where she said she would await word of her husband.

Theos Bernard
Associated Press

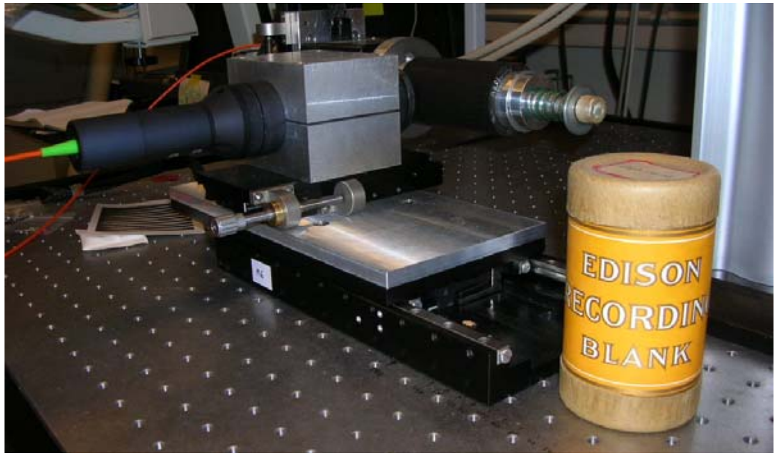
Oriental Philosophy from Colum-

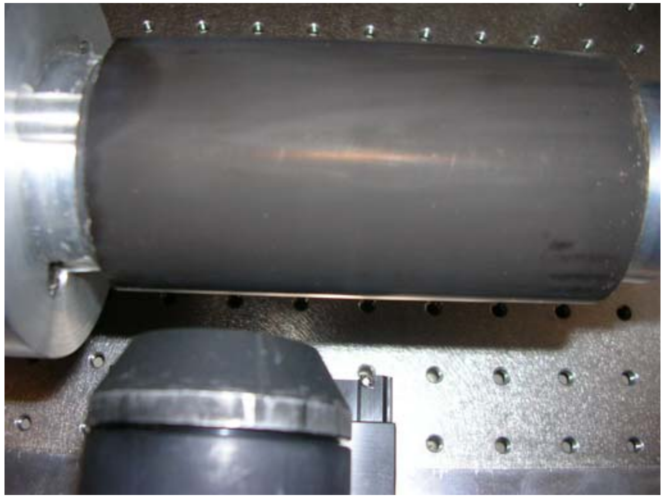
Damaged or Delicate Cylinders

- 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.





Sam Batwai, Alfred L. Kroeber, and Ishi

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