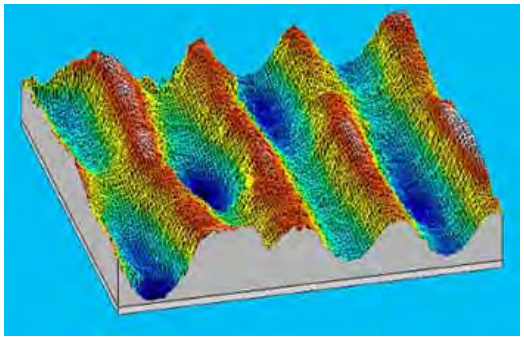
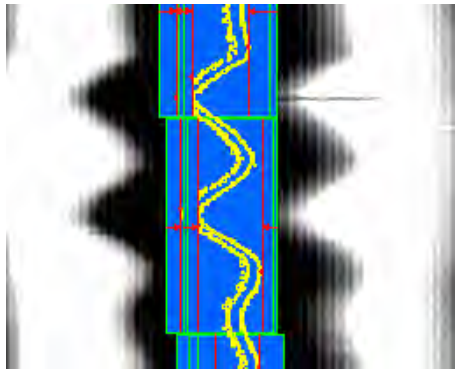




Imaging Methods Applied to Mechanical Sound Carrier Preservation and Access

Lawrence Berkeley National Lab

www.lbl.gov

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

Collaboration and Support

Lawrence Berkeley National Lab: CH, Vitaliy Fadeyev, Earl Cornell, Bob, Nordmeyer, Jian Jin, Edwin Widjonarko
EIF Fribourg: Noe Lutz, Michel Yerly
Mitch Golden
Fantasy Studios: George Horn
Library of Congress: Peter Alyea, Larry Appelbaum, Dianne van der Reyden, Nels Olsen

---

Financial Support from the
Library of Congress,
National Endowment for the Humanities,
The Mellon Foundation,
National Archives
The John Simon Guggenheim Memorial Foundation
Department of Energy
Corporate equipment donations, discounts, loan, and services from Aerotech, Archeophone, JH-Technology, Keyence, Microphotonics, National Instruments, Navitar, Newport, STIL, Uniforce, Veeco, Vidipax, Visicon

Introduction

- We are developing methods of optically recovering mechanical sound recordings **without contact** to the medium
- Address concerns of the preservation, archival, and research communities:
  - Preservation: The reconstruction of delicate or damaged media
  - Access: Mass digitization of diverse media

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

Non-Contact Digital Imaging

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

A “smart” copying machine for records

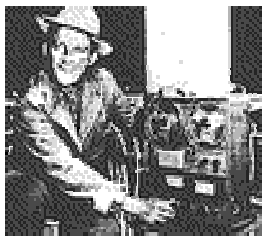
History

- 1859 Leon Scott invents *Phonoautograph* paper recorder
- 1877 Thomas Edison invents sound reproduction on tin foil *Phonograph*
- 1885 Bell and Tainter introduce wax cylinder
- 1887 Emile Berliner invents disc *Gramophone*
- 1925 Western Electric *Orthophonic* (electrical) system

  end of the "**Acoustic Era**"
- 1929 Edison production ends, lacquer transcription disc introduced
- 1947 Magnetic tape in production use, Ampex 200A
- 1948 33 1/3 rpm LP introduced
- 1958 Stereophonic LP on sale, uses 45/45 system
- 1963 Cassette magnetic tapes
- 1982 Compact Disc (*CD*)

  end of the "**Analog Era**"
- 2001 Apple *IPOD*

Discos fonográficos Pathé
Caras y Caretas (7/7/1908)



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

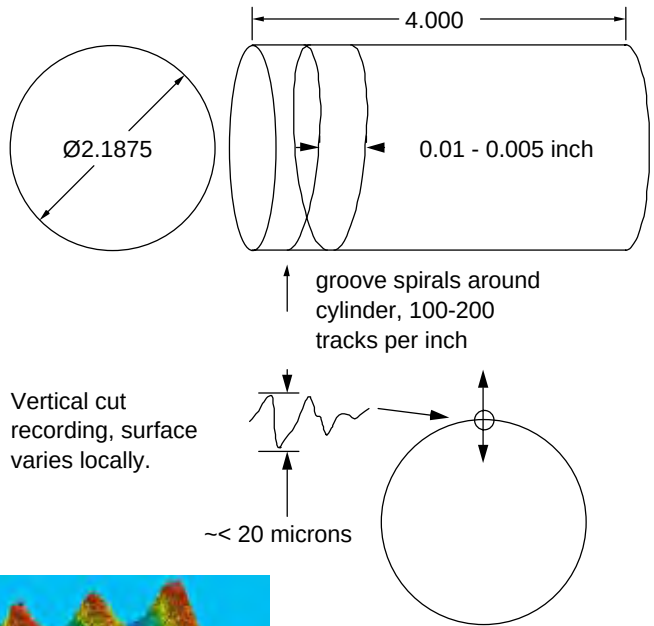
Wax and plastic cylinders: mold growth, wear, breakage

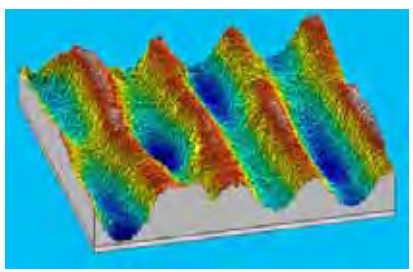
Plastic belts: dictation, monitoring (1940’s-60’s), folds, cracks, wear

Metal stampers

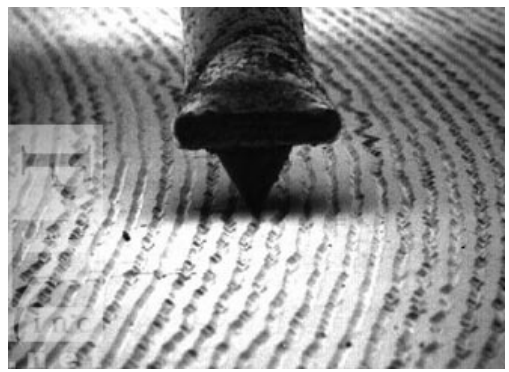
Mechanical Recording Principles

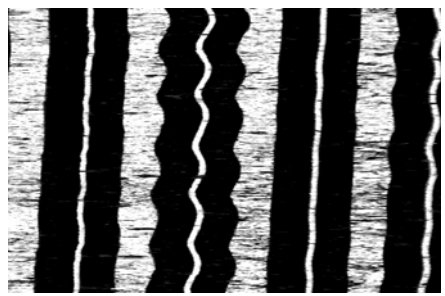
Cylinder: groove varies in depth (hill and dale)

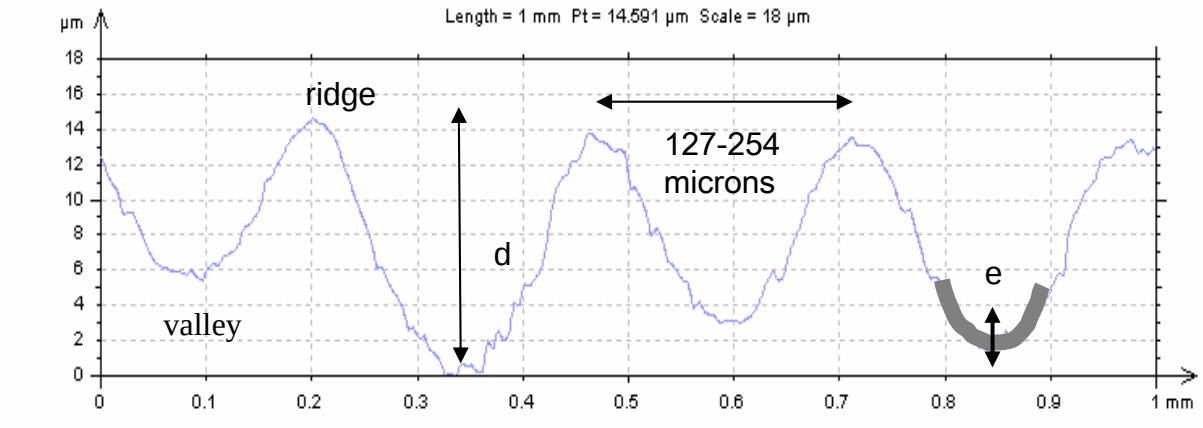




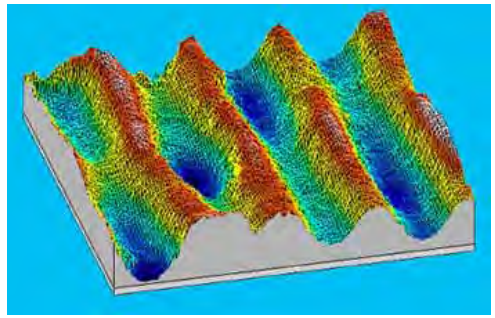
Disc: groove moves from side to side



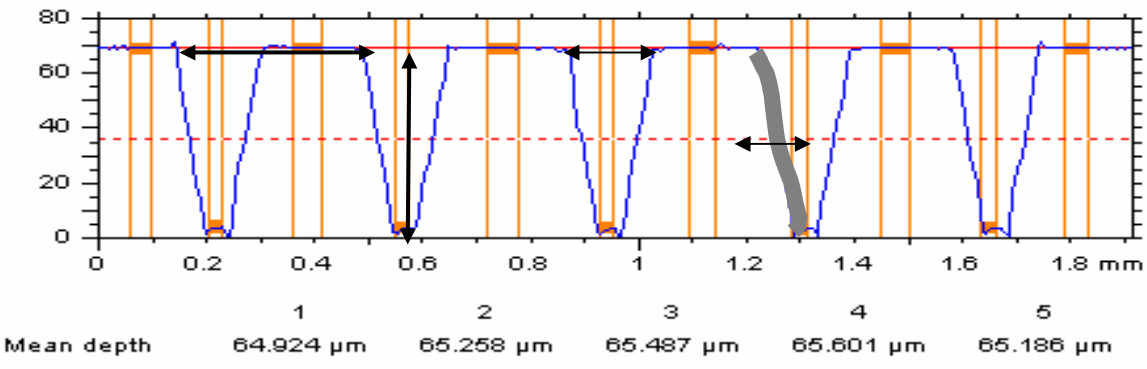




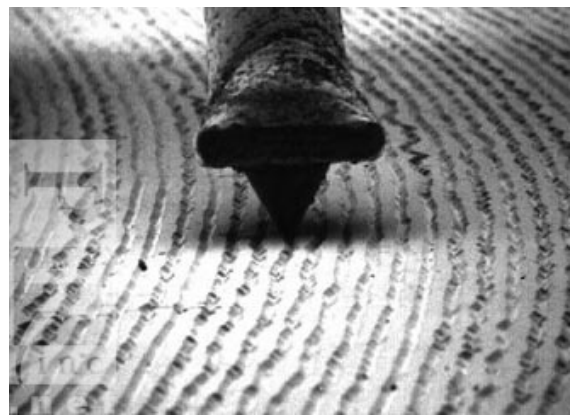
Cylinder surface



400 µm 150 µm



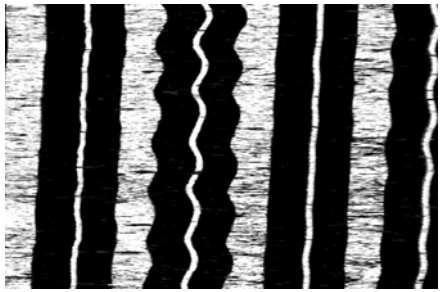
Disc surface



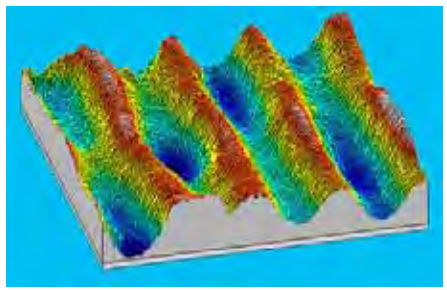
Debate during acoustic years between cylinder (constant surface speed) and disc (ease of manufacturing and storage) technologies.

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



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

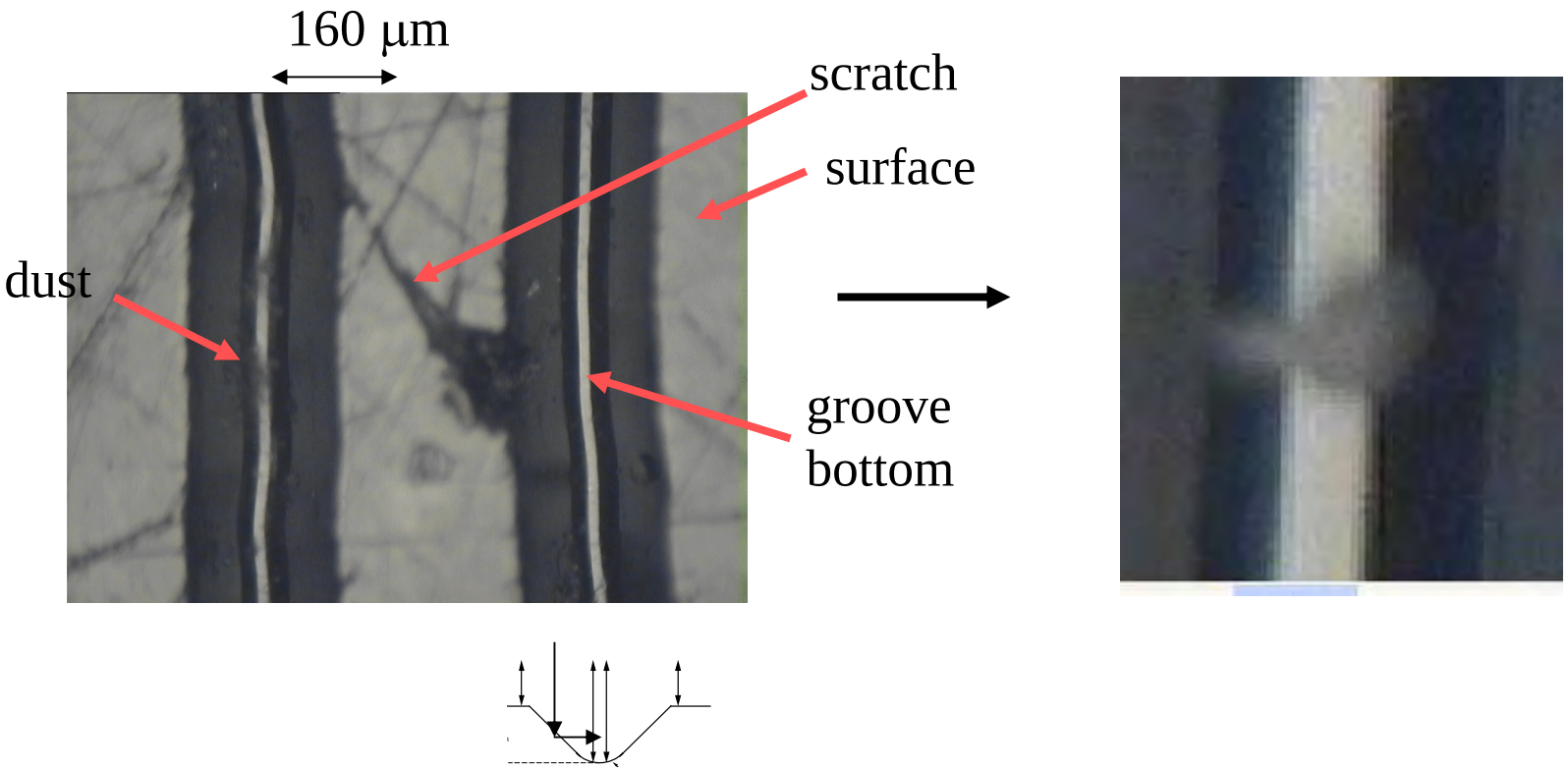


Surface profile of a wax cylinder:
A three dimensional image “3D”
is <u>required for vertical</u> cut grooves

The Method

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

2D Imaging: Electronic Camera

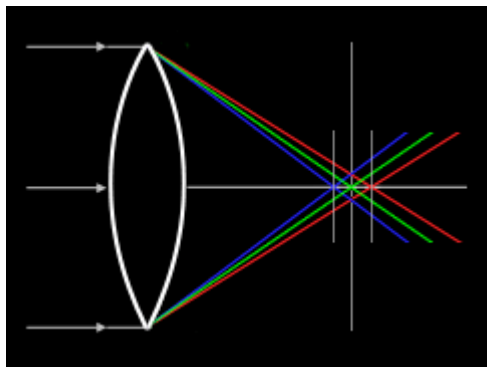


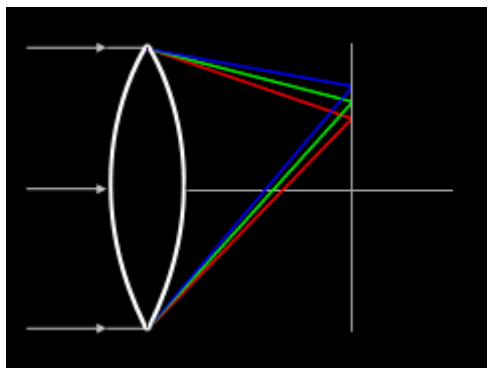
- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface
- Coaxial illumination

Speed and Data

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

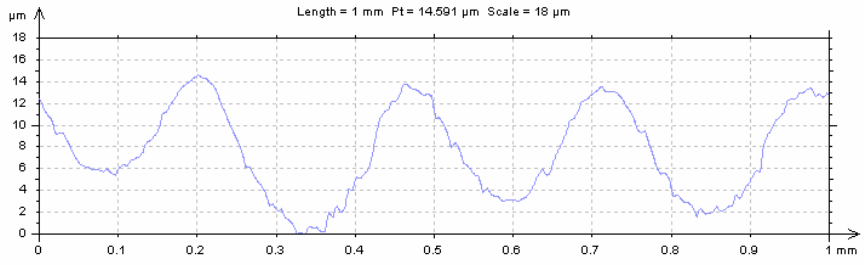
Chromatic Aberration



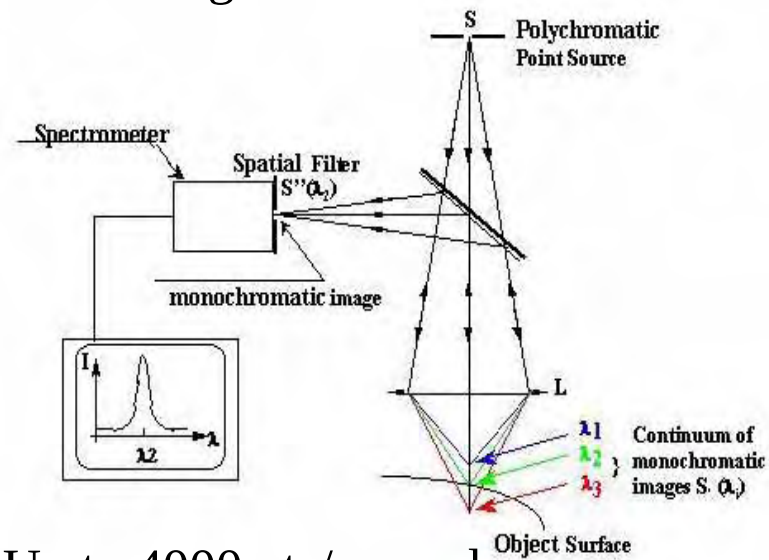


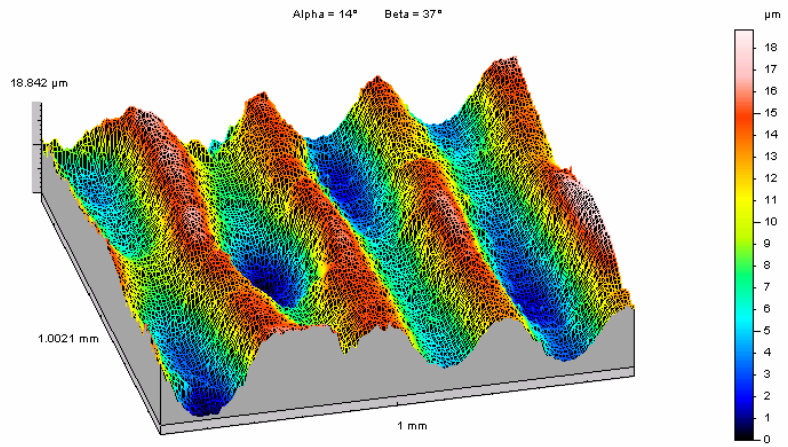
3D Imaging: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.



Point by point scan
0.01 degree = 96 KHz

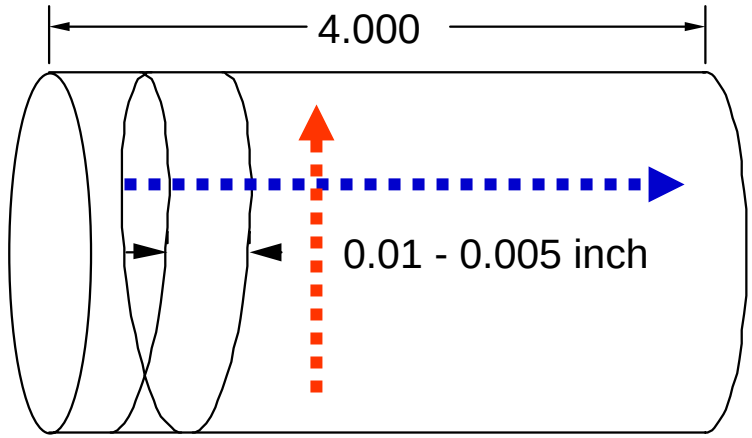




Up to 4000 pts/second
~ 5 micron point size

Surface of an Edison cylinder

Speed and Data

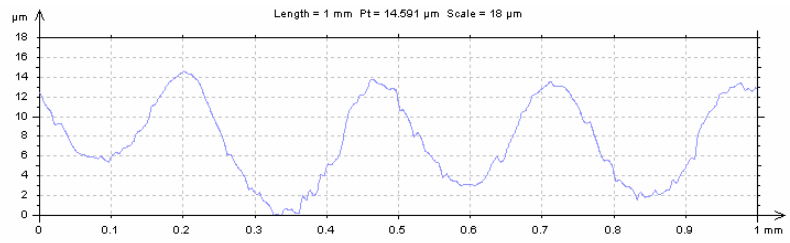


Fundamental drivers are: probe rate, grid (time x profile)

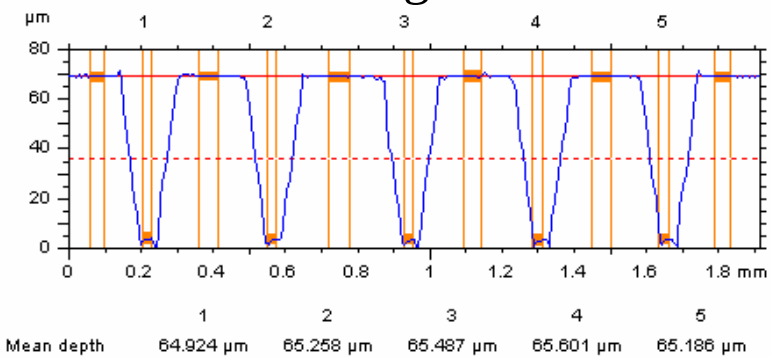
Speed and Data

- 3D scans for vertical cylinders
  - Depends upon grid, probe rate, recording & surface characteristics
  - High sampling: 24-80 hours
  - Factors of 2-4 may be available soon
- 3D for deep groove lateral discs
  - Much slower probe rates are probably required

Vertical groove



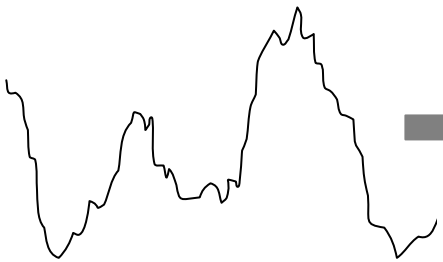
Lateral groove

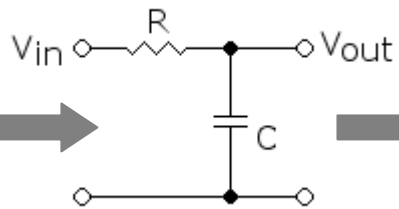


Key 3D issues are slope and depth

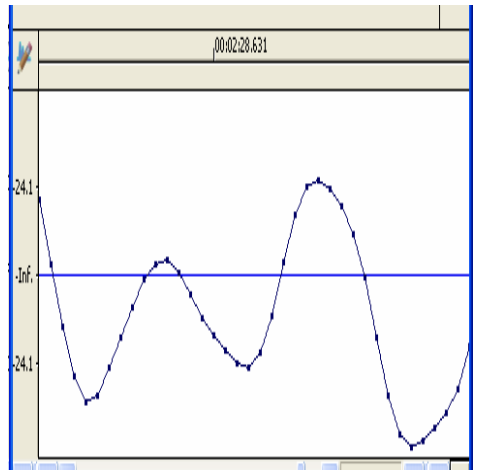
Low-pass filter
$f_0 < f_{sample}/2$

Analog waveform





ADC

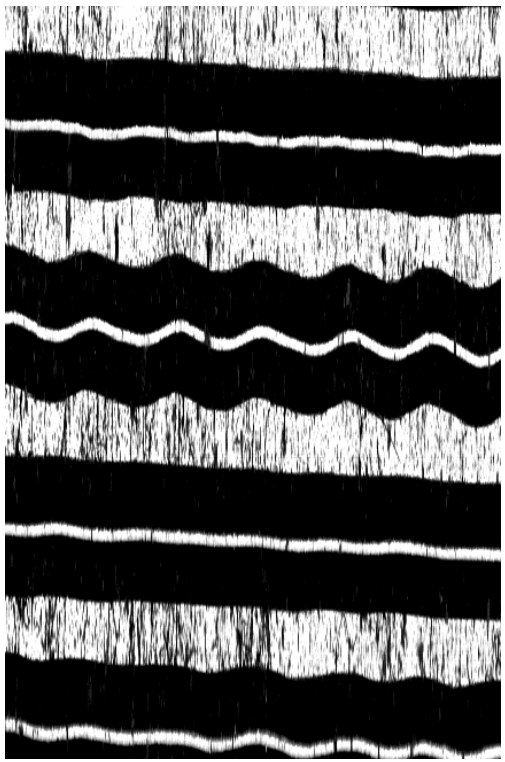


Commercial CD: 16 bits, 44.1 KHz
Archive spec: 24 bits, 96 KHz

Segmented image determines sampling

Time

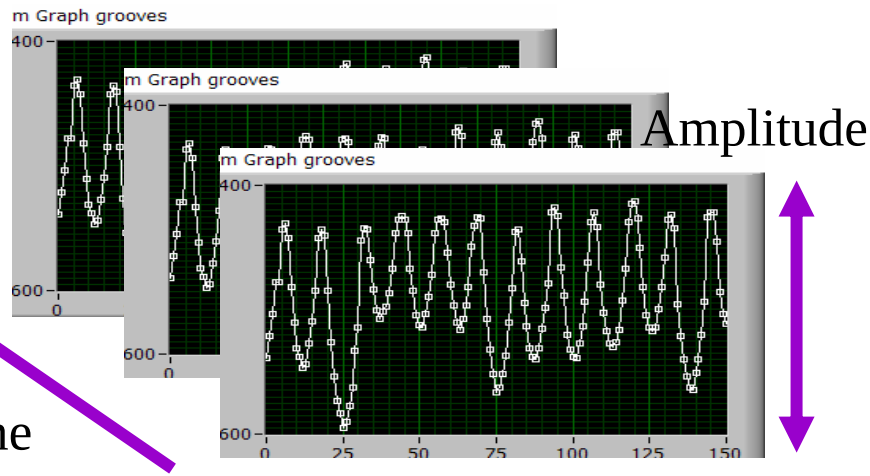
Amplitude



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

Easily time sample to 300 KHz

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



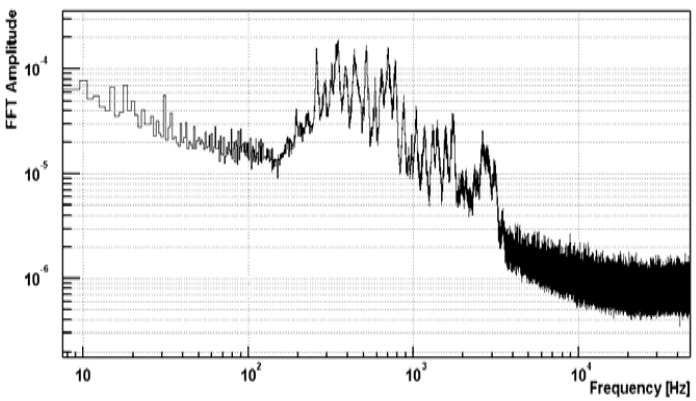
Issue of Aliasing

- Sampling theorem

1. Sample at 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?



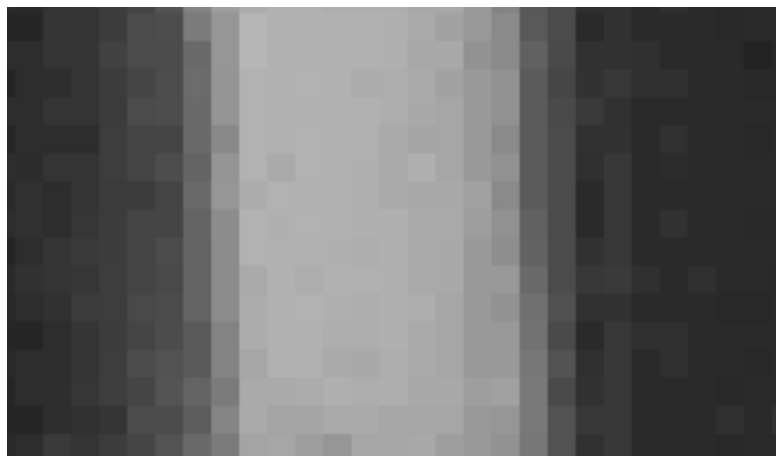
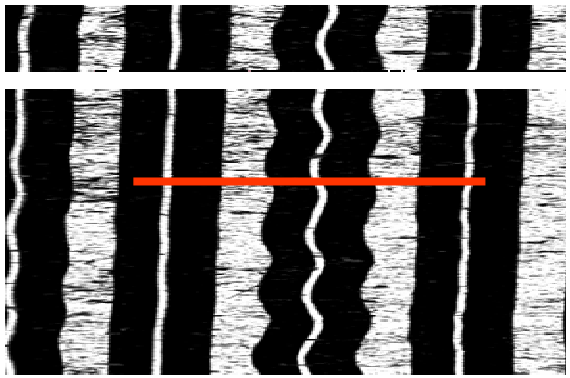
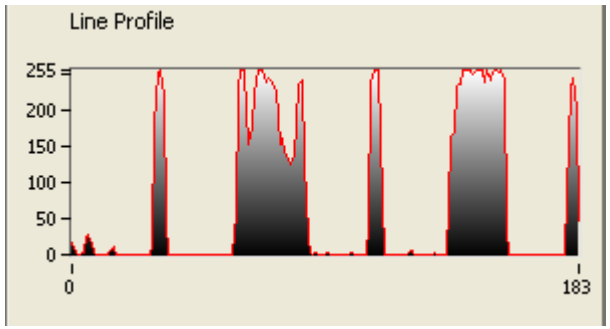
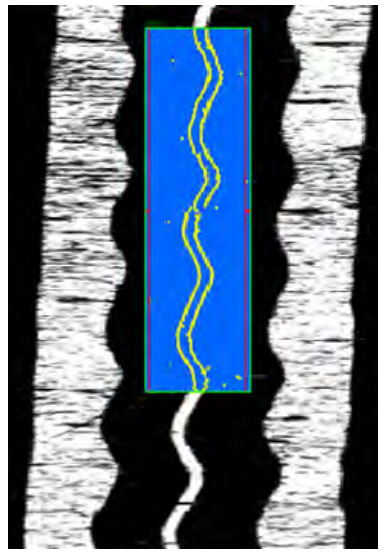


Image Analysis

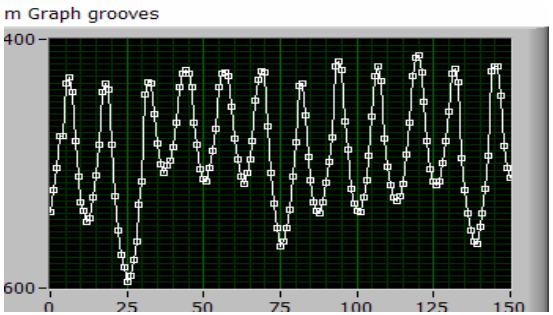
2D







3D

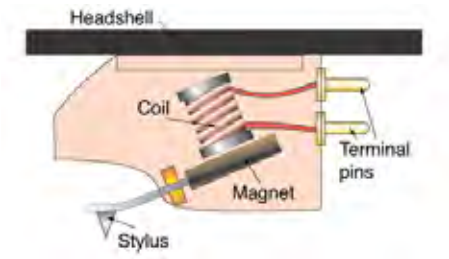


Fits to data provide estimate of depth

Groove geometry is unique and provides a powerful constraint on data

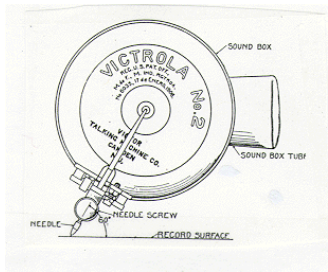
What is the relationship between "groove" and sound?

Electro-magnetic case

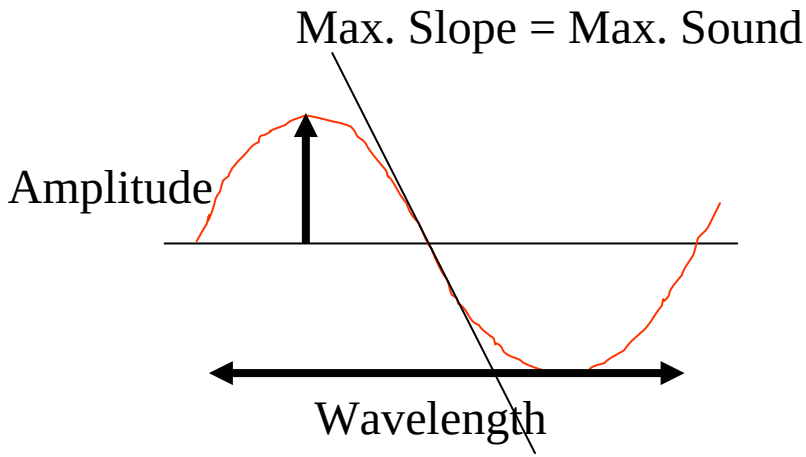


induction

Acoustic case



Diaphragm is over-damped to provide flat response

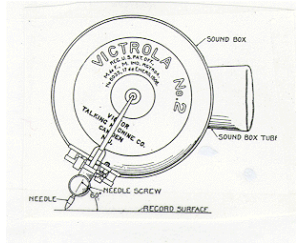


Sound = Stylus Velocity

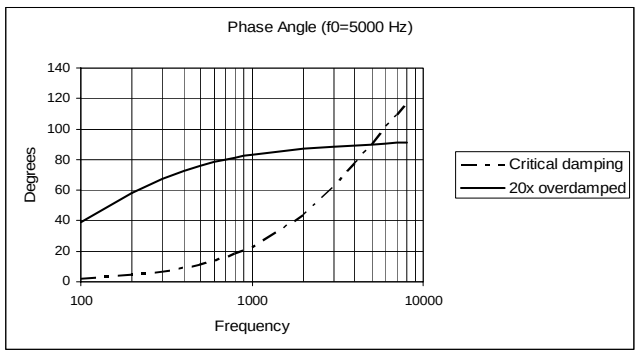
("constant velocity condition")

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

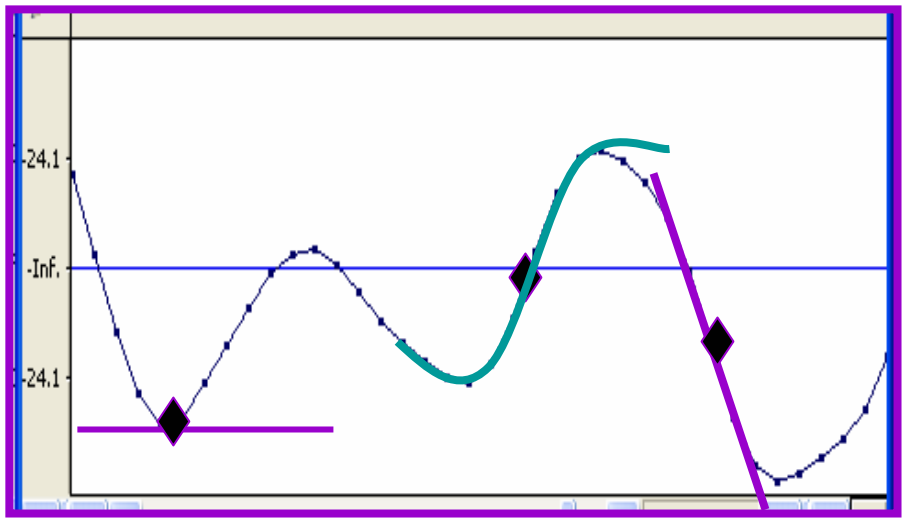
Acoustic Case

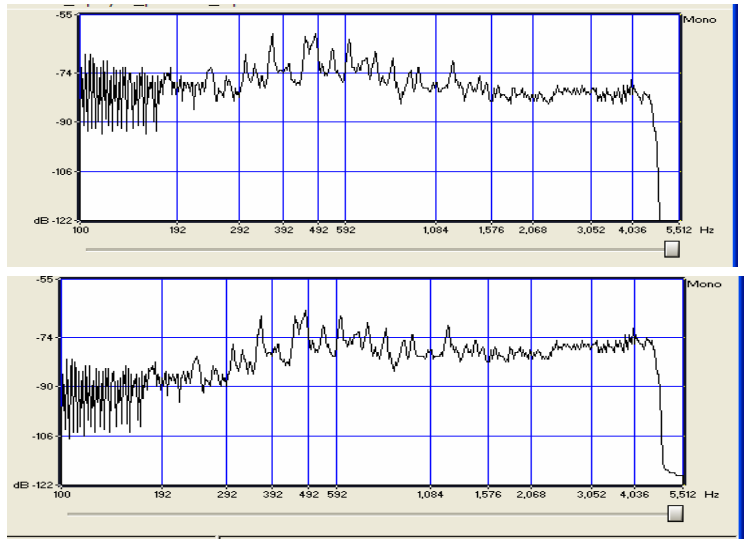


- Horn extends response (of small diaphragm) to lower frequencies
- Plane waves: pressure and velocity are proportional and in-phase
- Horn supports plane waves: true above a cut-off frequency for sufficiently large horn, depends also upon profile
- Diaphragm is a driven harmonic oscillator
- Want "flat" 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



Stylus Velocity and Filtering





- **Finite Difference Method "FD"**
- Calculate slope at each point
- Point set imposes high frequency rolloff
- Slope (at n) = A(n-2) – A(n+2) / interval
- **Local Fit Method "Pnn"**
- Fit polynomial to sets of points
- Complex high frequency effect

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

Numerical Differentiation and Filtering

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

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

The filtering factor:

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

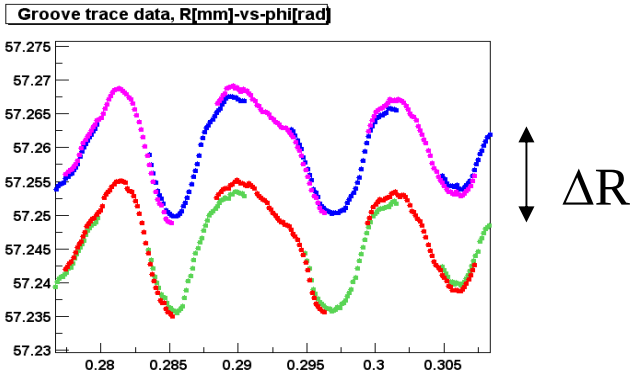
Perform the differentiation and filtering in a single processing step by:

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

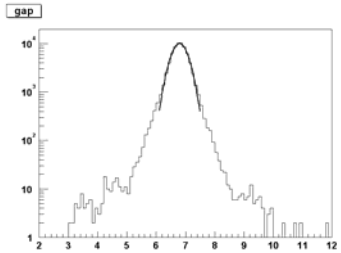
Comparison

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

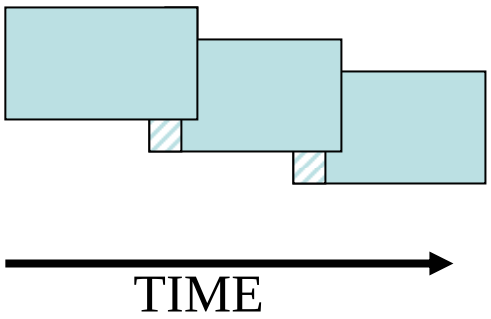
- Non-contact
- Robust – wax, metal, shellac, acetates…
- Effects of damage and debris reduced by image processing
- Re-assemble broken media
- Resolve noise in the “spatial domain” where it originates.
- Use of groove geometry.
- Effects of skips are reduced.
- Distortions (wow, flutter, tracking errors,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



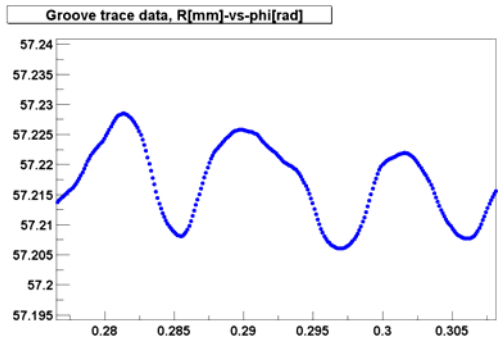
ΔR distribution



Width across groove bottom

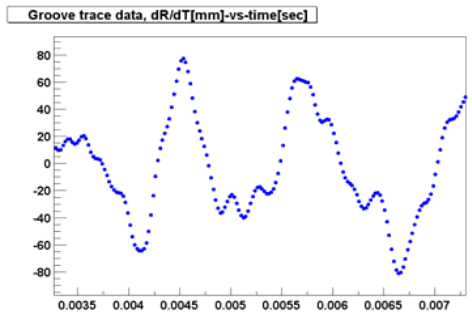


Measurement spacing along time axis ~ 66 KHz



Align
Average
Filter using ΔR<cut

Measure slope at each point (stylus velocity)



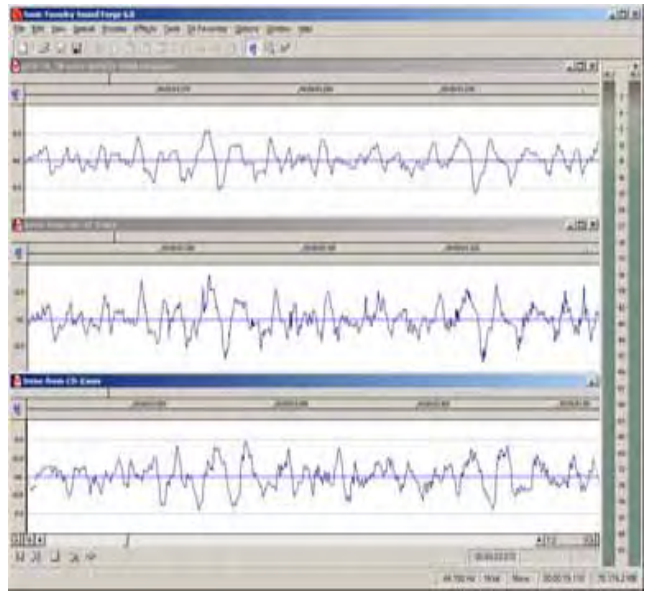
Sound Comparison

"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***.

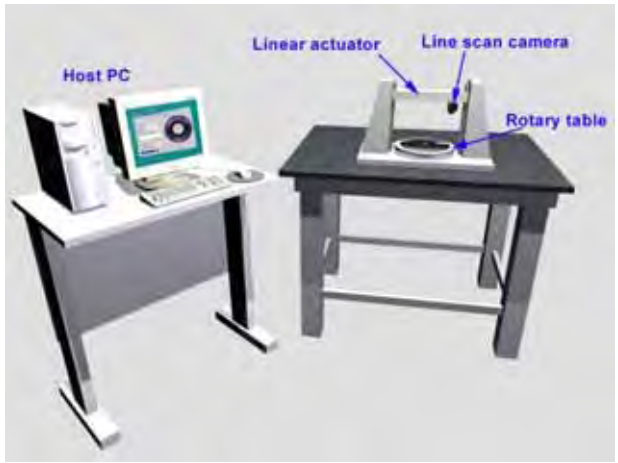


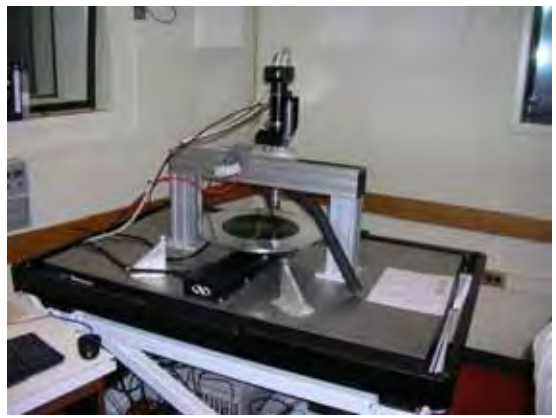
Projects Underway

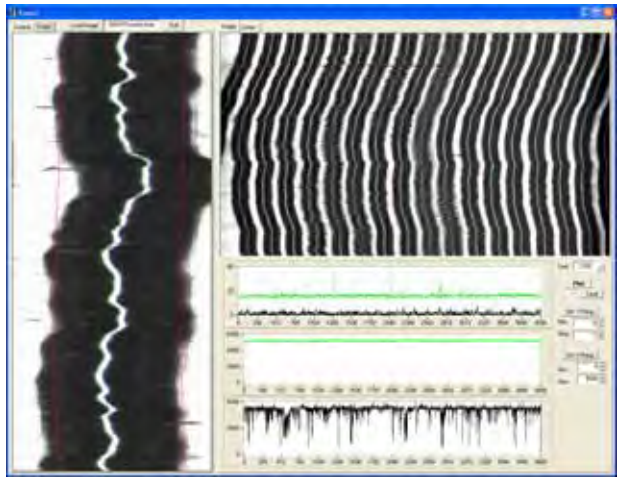
- Concept was tested 2002-2003 leading to interest and support from the Library of Congress and others.
- IRENE: a fast 2D optical scanner for disc records
  - Digital access to the most common media + special formats
  - Installed at the Library of Congress 8/2006
- 3D scans on “Edison” cylinders
  - 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

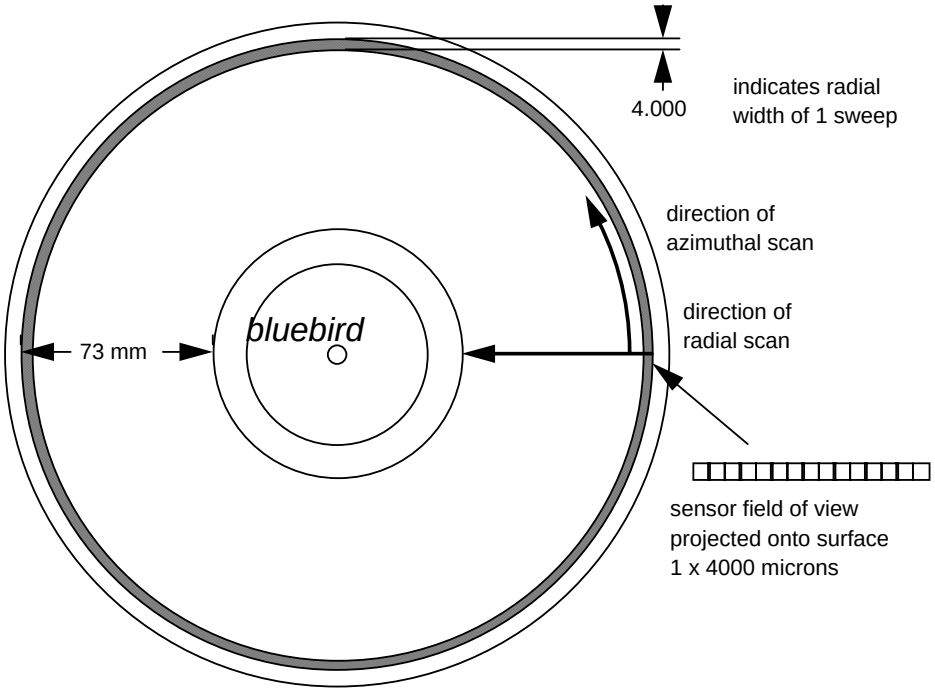


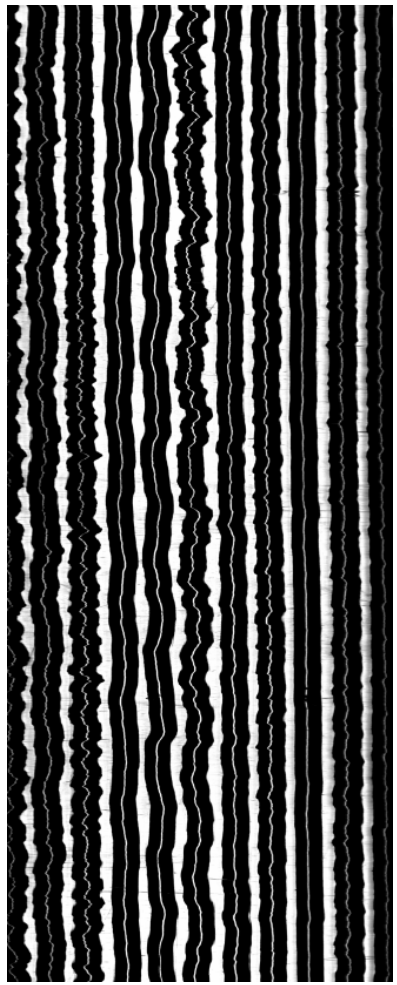


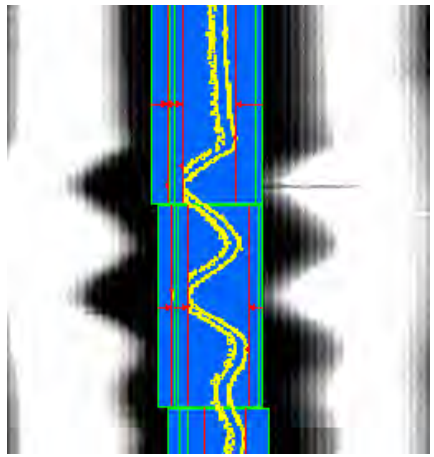


- Funded by NEH in 2005, installed at Library of Congress 8/2006
- ~1 year development and construction
- Experimental “production” machine and test-bed for future development
- Emphasize throughput and diversity (access), scan time ~10-15 minutes
- Provide statistical measures of media condition
- Currently under evaluation

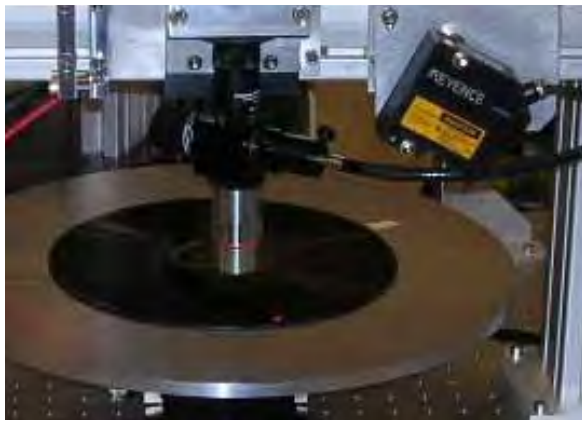
Line Scanning: disc is in motion

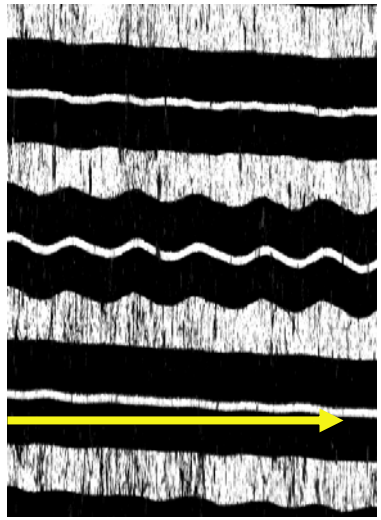




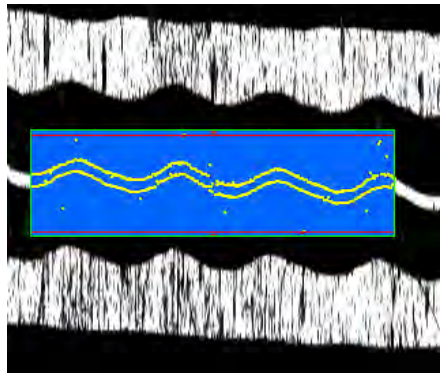


- 6000 pixels@15 K lines/s
- 7.6 x 10^5 lines/outer ring
  - **390 KHz max sampling**
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.



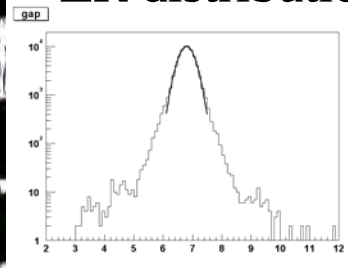


Time
Pixels = 104 KHz

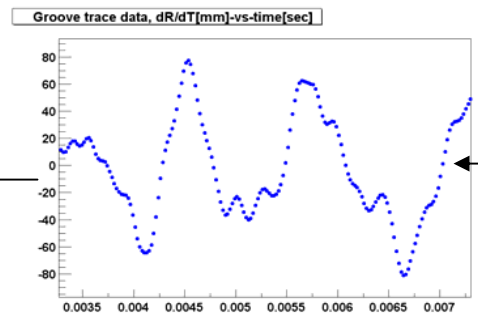


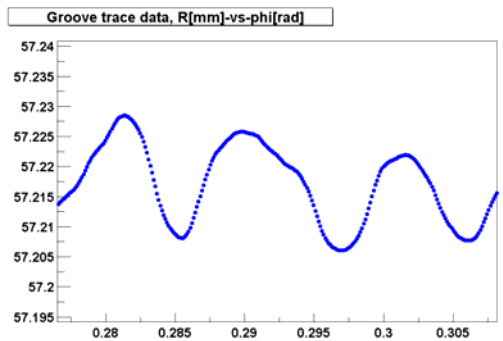
Width across groove bottom

ΔR distribution

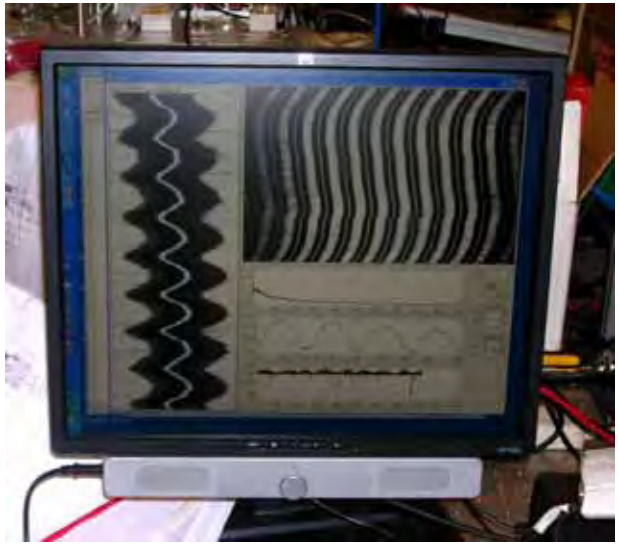


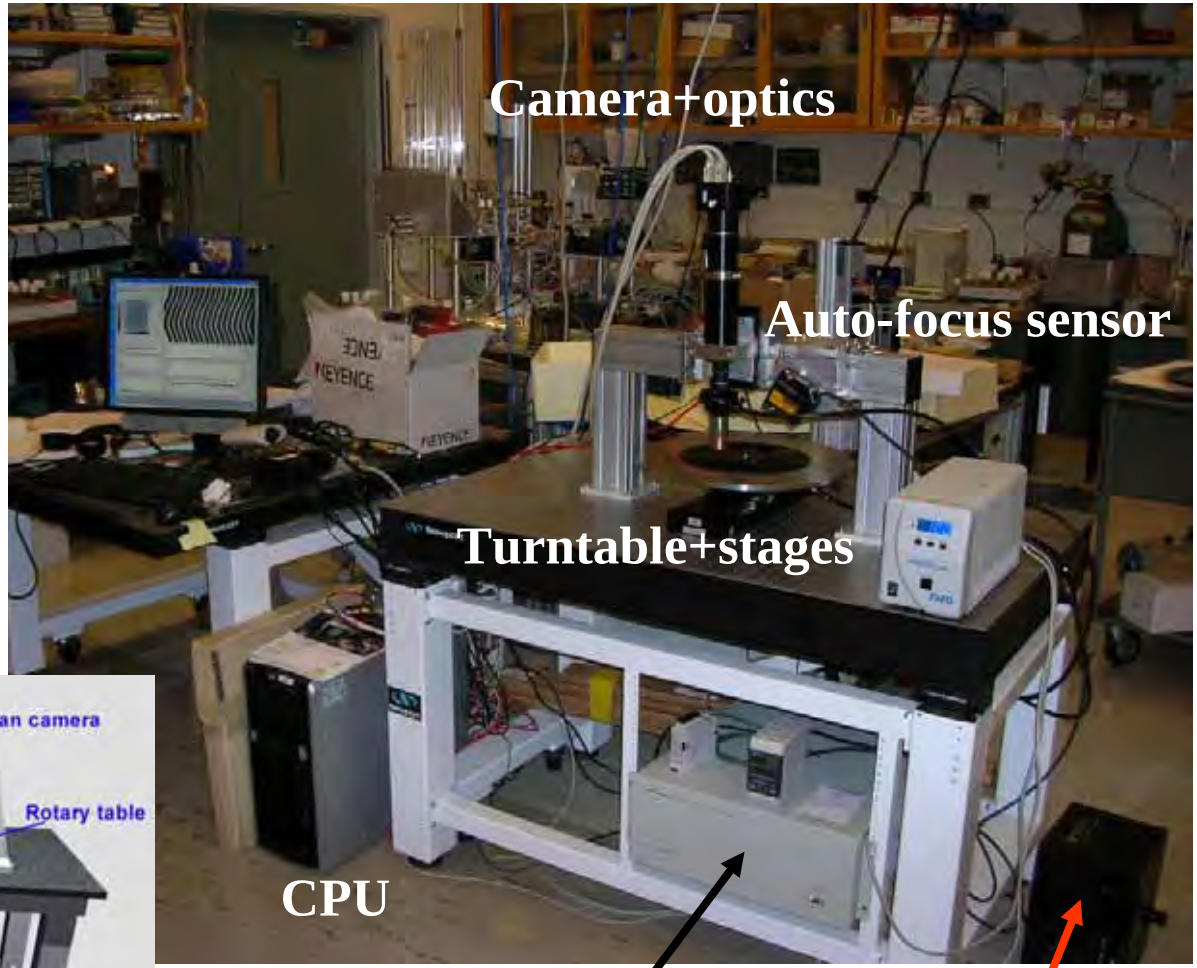
Measure slope at each point (stylus velocity)

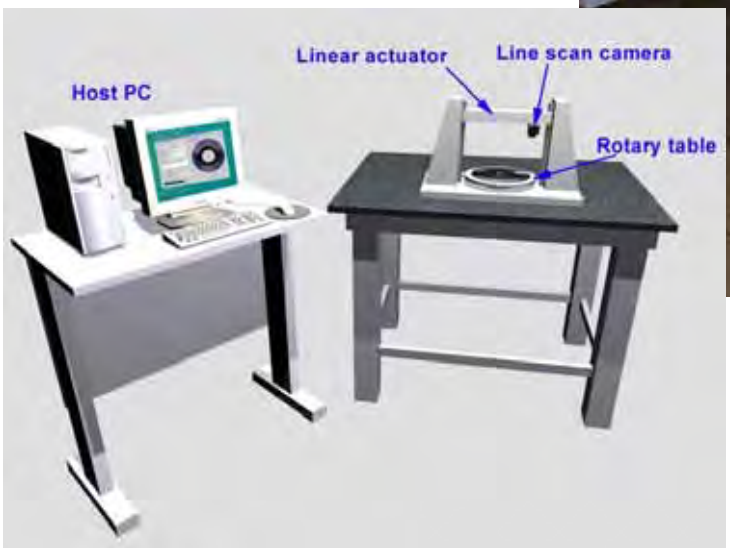




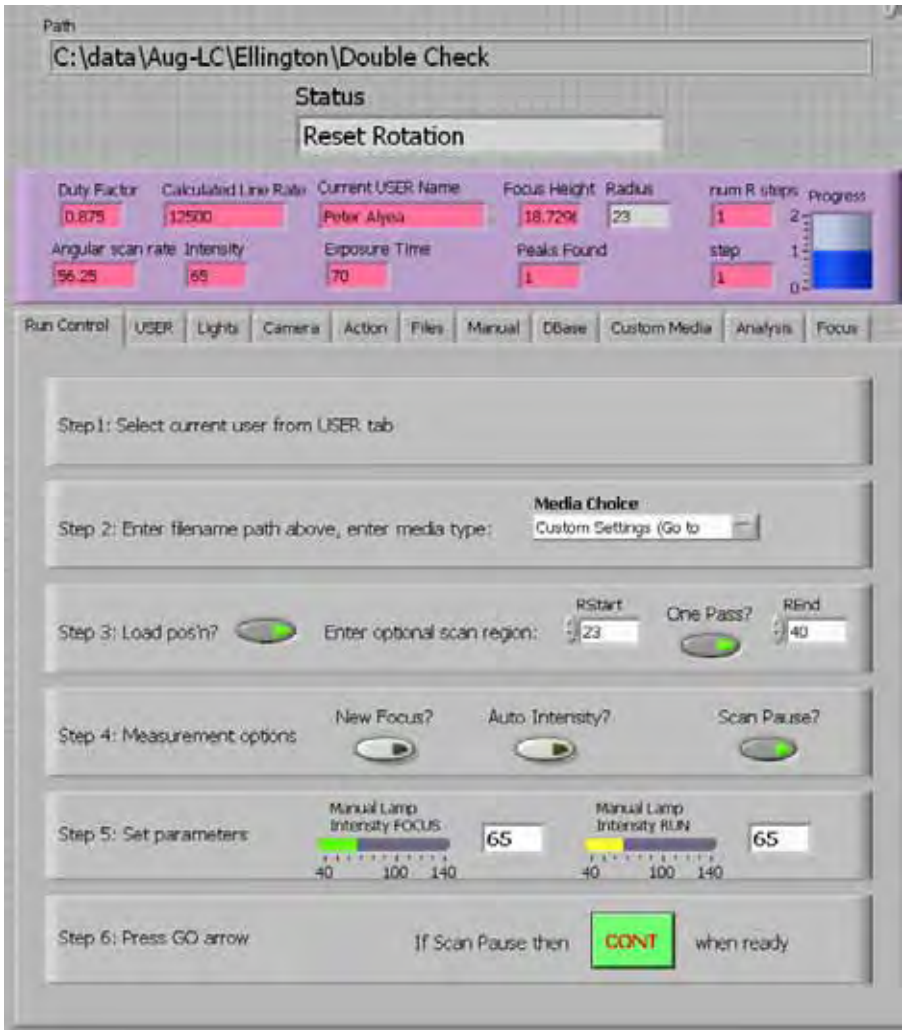
Average
Filter using ΔR<cut

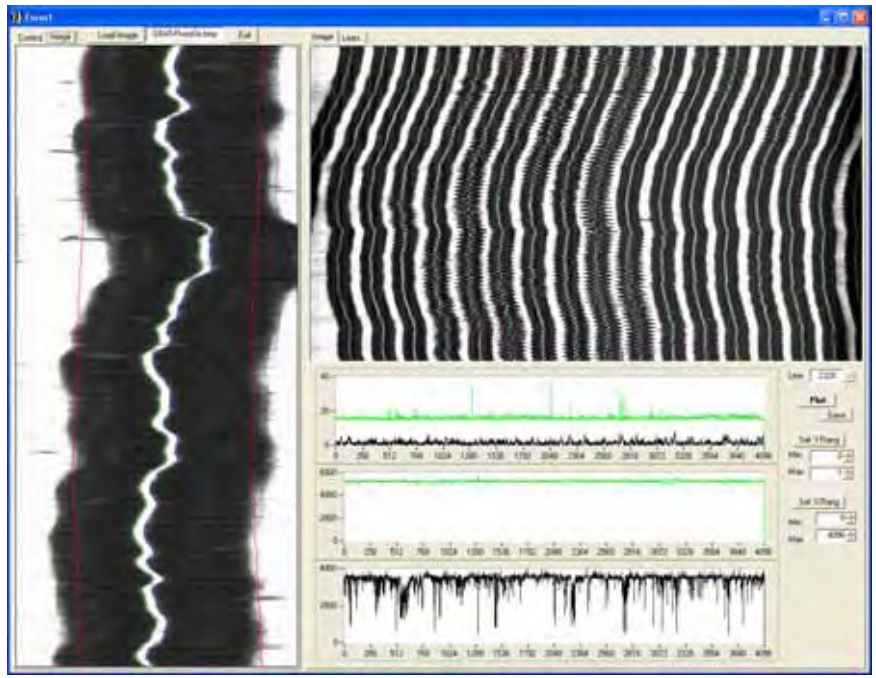


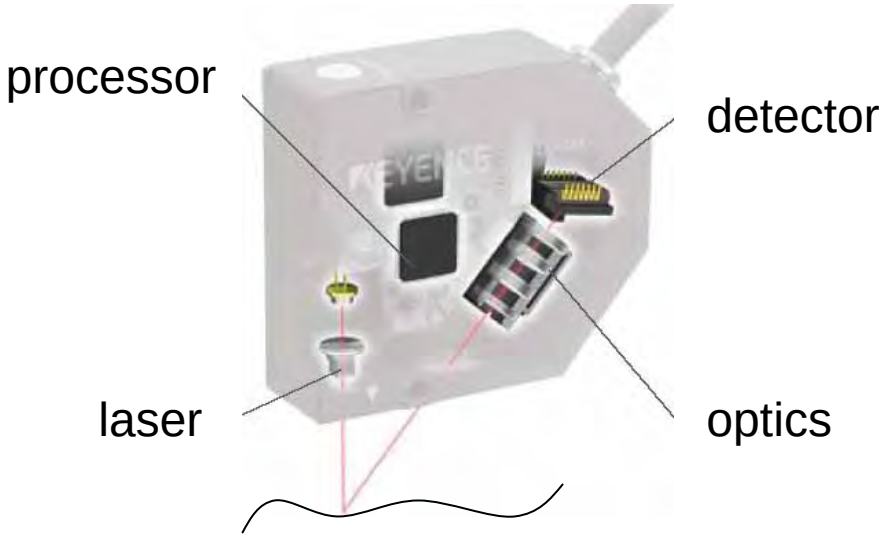

Camera+optics
Auto-focus sensor
Turntable+stages
CPU
Motion control
Light source

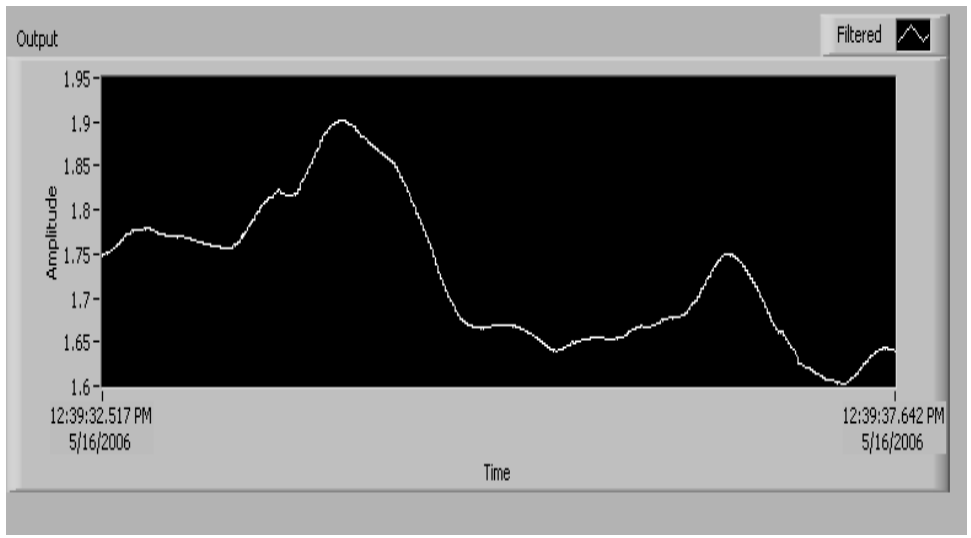

Linear actuator
Line scan camera
Host PC
Rotary table

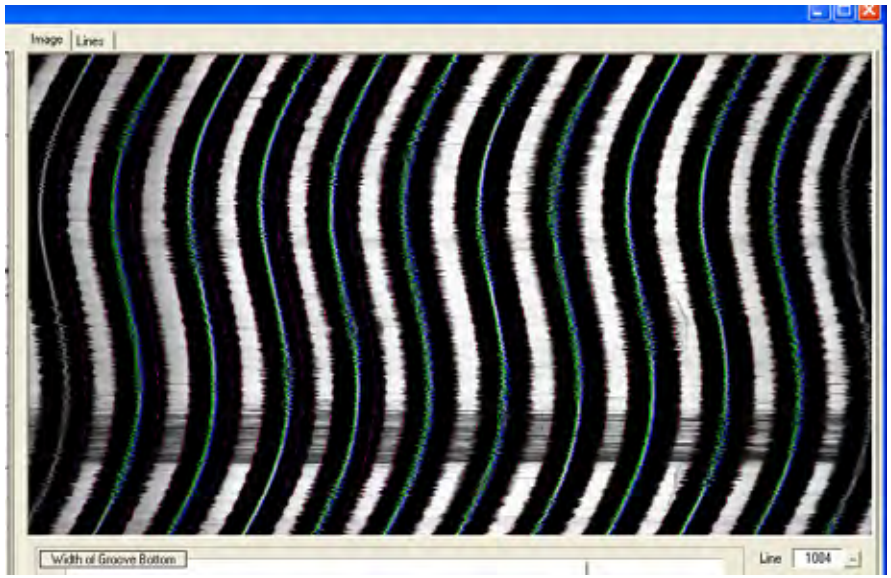
Control and Analysis Codes





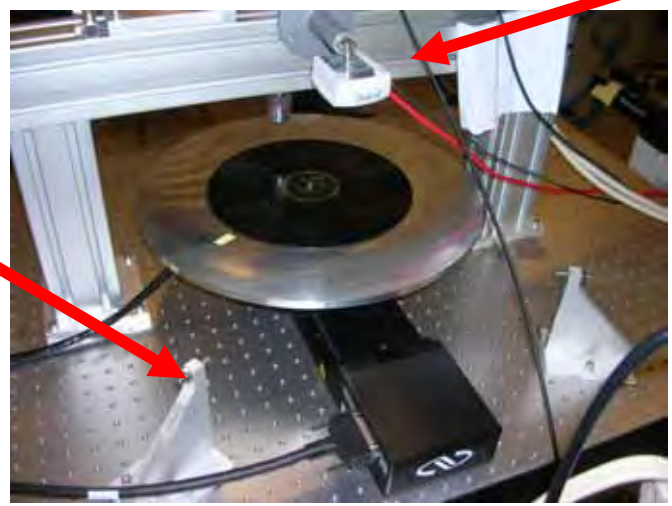

processor
detector
laser
optics


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

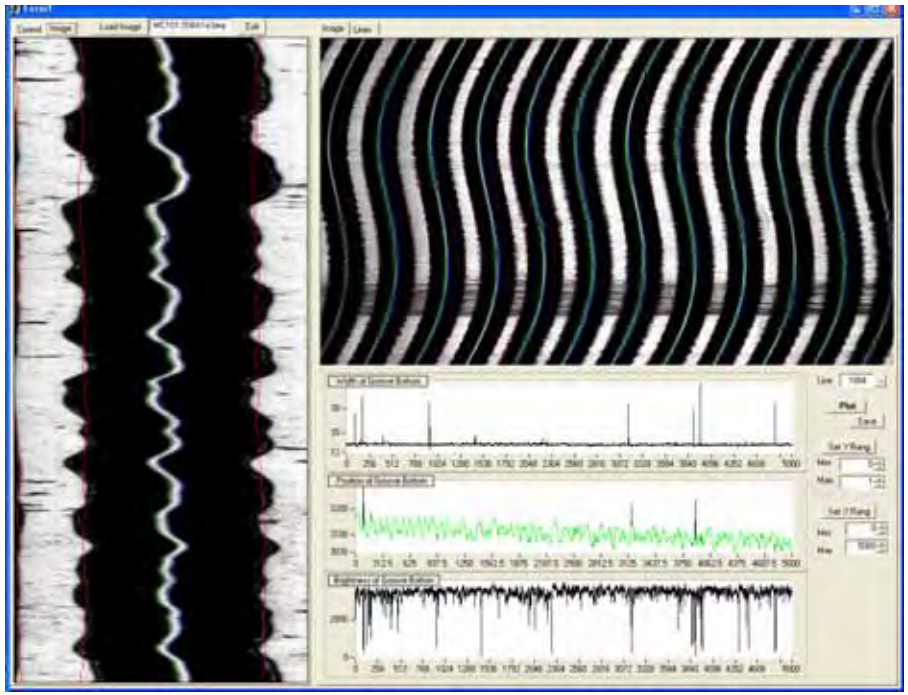


Label camera

Eccentricity control

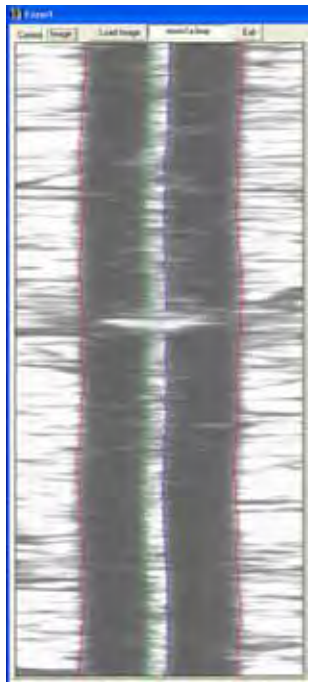


Groove Images

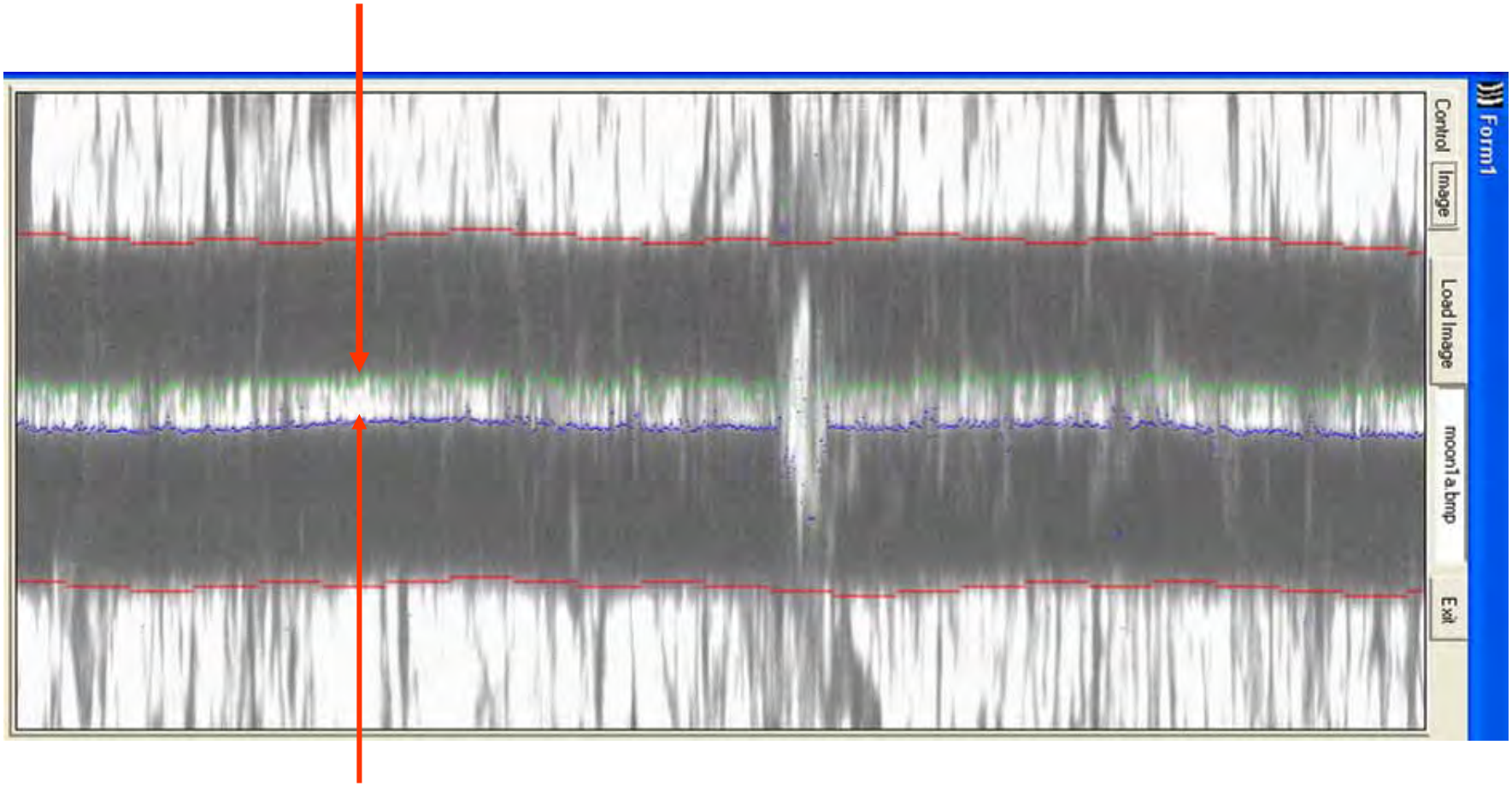


Lacquer disc

Shellac with moderate wear



Poor quality shellac, acoustic recording


Form1
Control
Image
Load Image
moon1a.bmp
Exit

Status

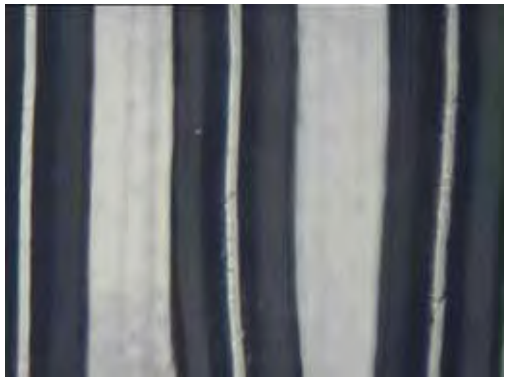
- Hardware configured and scanning
  - 15 minutes for a 3 minute disc but >50% is overhead
- Main control, logging, and analysis code runs
- Main issues have been illumination and field of view, uniformity
- Can process most scans and extract sound
  - Significant study of parameters still in process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

Testing and Validation Phase

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

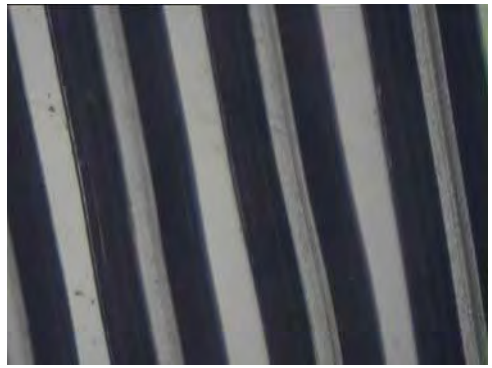
Media Condition Survey on LC Samples

good 65%



poor 10%

good lacquer



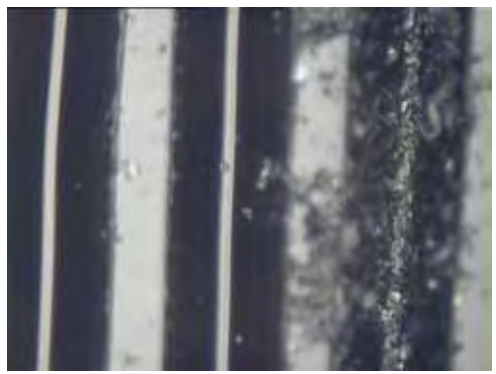
fair 25%

Multiple edges

fair

Rough groove bottom

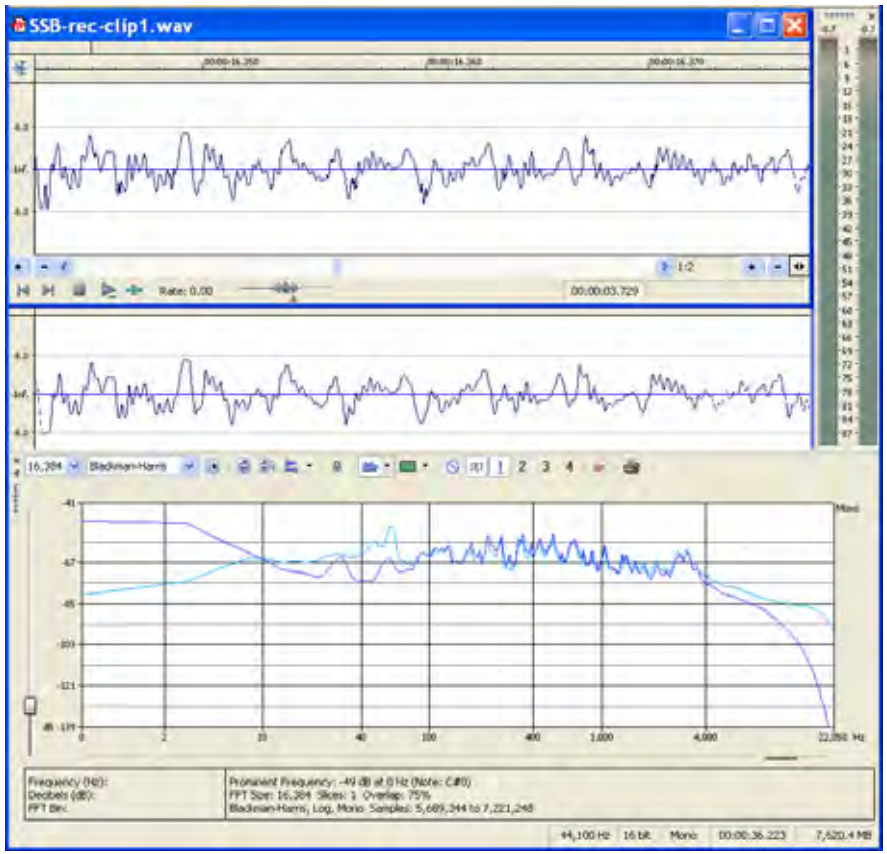
exudated lacquer



Test Scan Examples

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

The Star Spangled Banner: Kate Smith

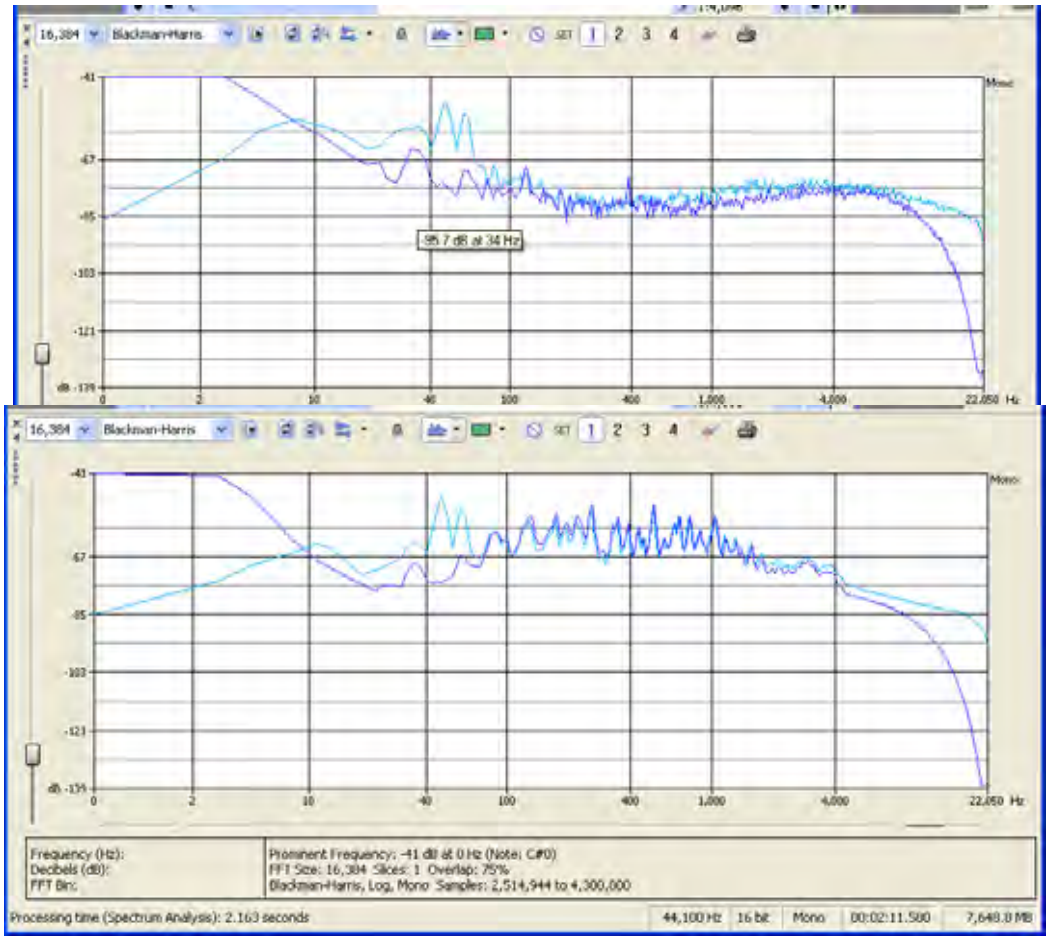


stylus

IRENE

78 rpm shellac disc with moderate wear,
RIAA curve applied

Goodnight Irene: Weavers 1950



Noise spectra

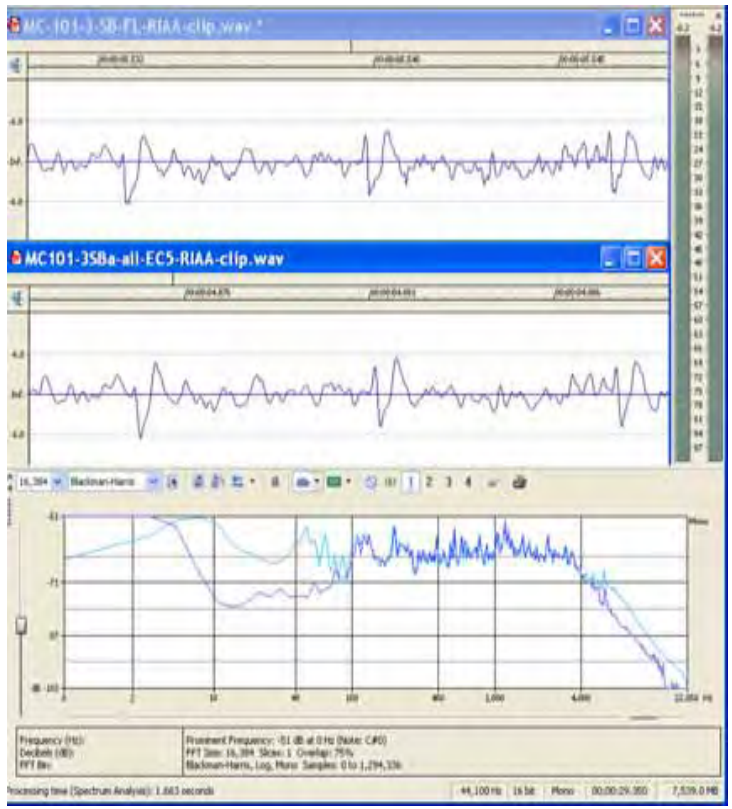
stylus

IRENE

Studio Test 1947

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

Lacquer disc, RIAA EQ



stylus

IRENE

Acoustic Recordings, Worn

Dirty and worn

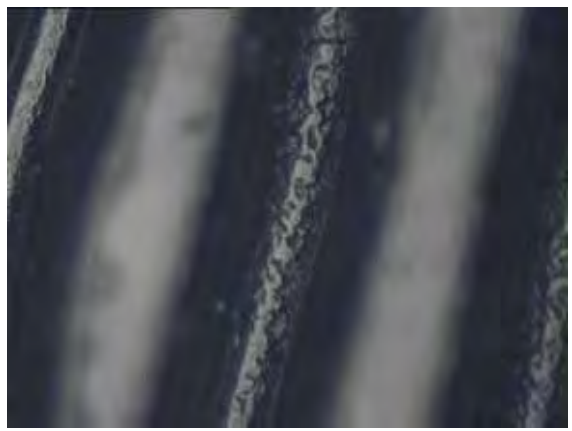
When You and I Were Young, Maggie
Composer: Johnson and Butterfield
Performed by Charles Harrison
Victor 17474-B

Stylus version

IRENE test scan

Poor image quality

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



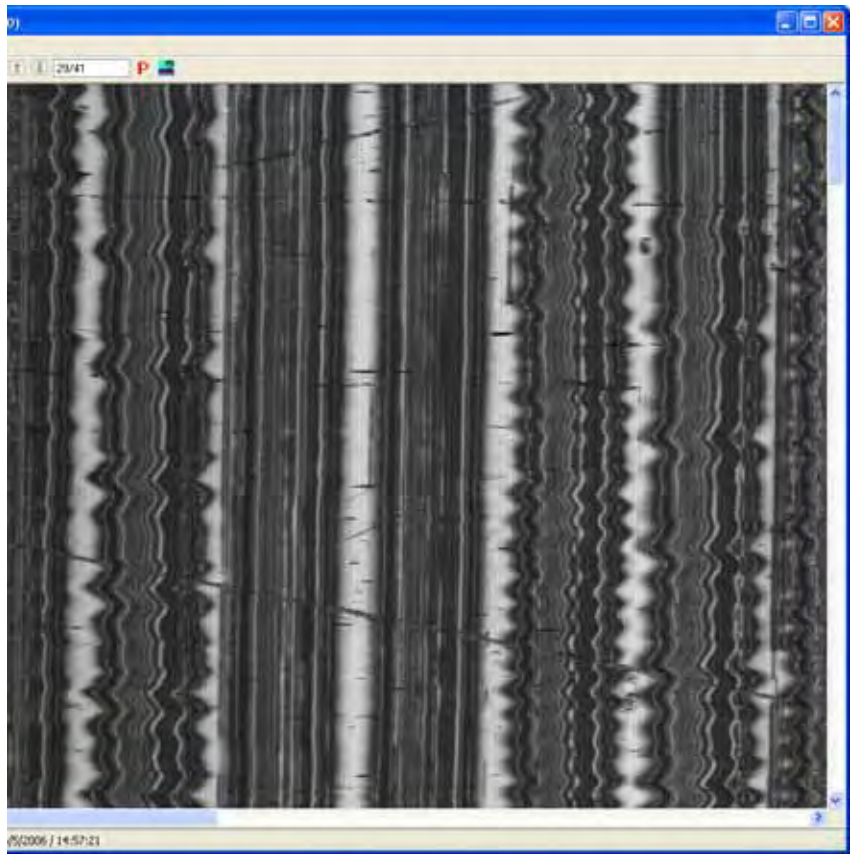
Classified POOR in initial media survey

Stylus version

IRENE test scan

Memovox Disc

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



Interesting Lacquer Discs

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

78 rpm acetate,
Theos Bernard,
interview, 1929

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. 18.

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.

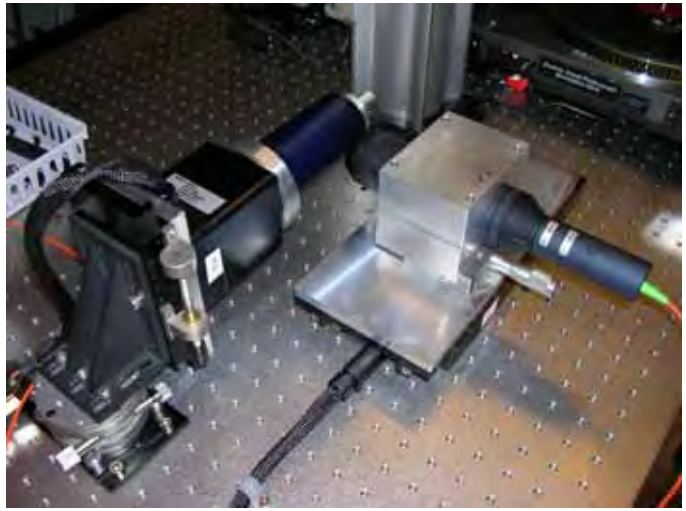
Theos Bernard

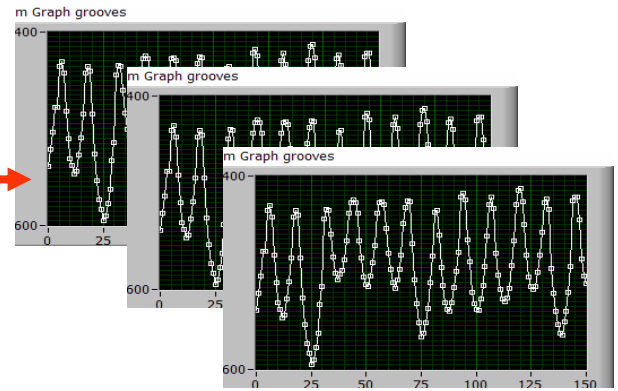
Oriental Philosophy [illegible] Columbia

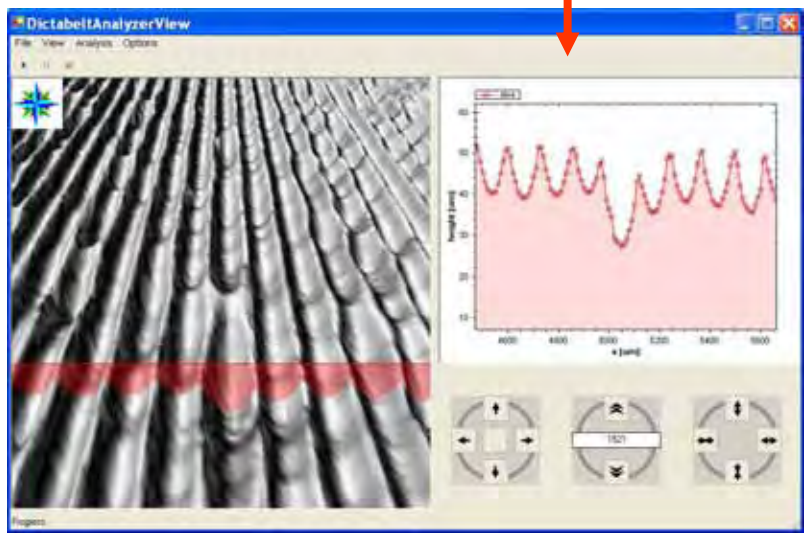
Cylinder Scans

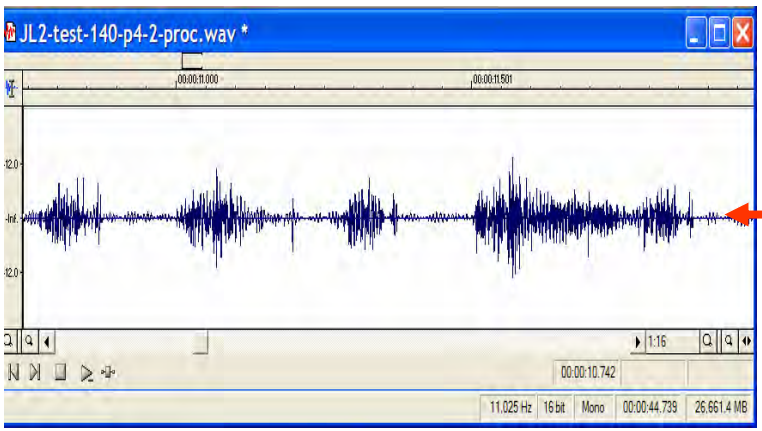
- Cylinder History
  - 1877 Aluminum foil
  - 1885 Soft wax for original recordings and dictation
  - 1902 Hard wax molded, commercial
  - 1908 Cellulose molded, commercial “Amberols”

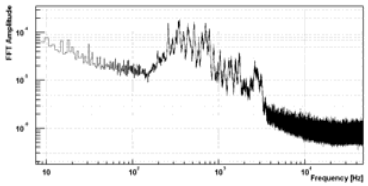

EDISON
GOLD MOULD
RECORDS
ECHO ALL
OVER THE WORLD



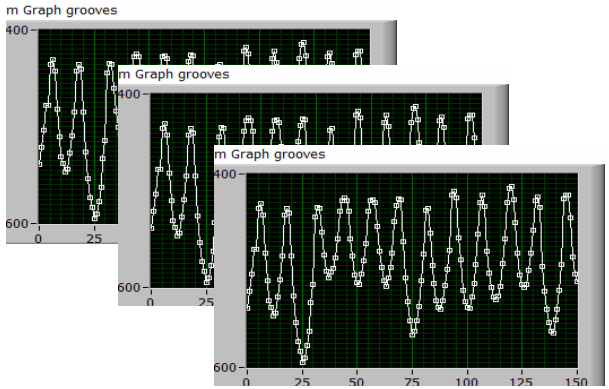

m Graph grooves
400
600
0
25
m Graph grooves
400
600
0
25
m Graph grooves
400
600
0
25
50
75
100
125
150


DictabeltAnalyzerView

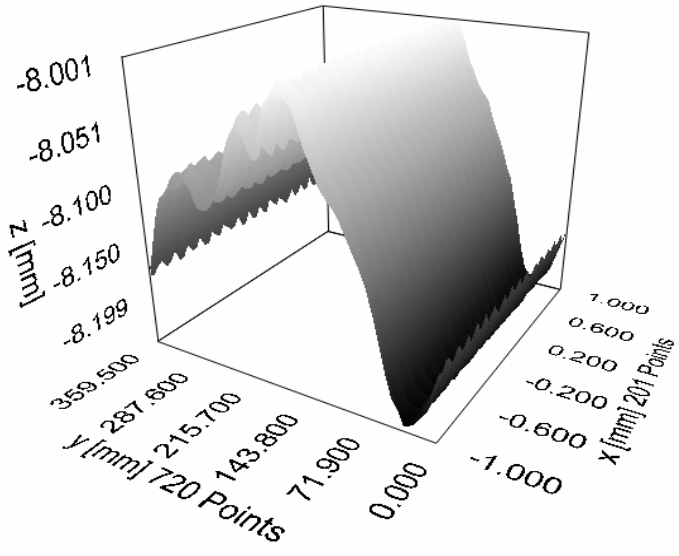

JL2-test-140-p4-2-proc.wav *
00:00:10.742
11,025 Hz
16 bit
Mono
00:00:44.739
26,661.4 MB



Sample at 96KHz to minimize effect of aliasing

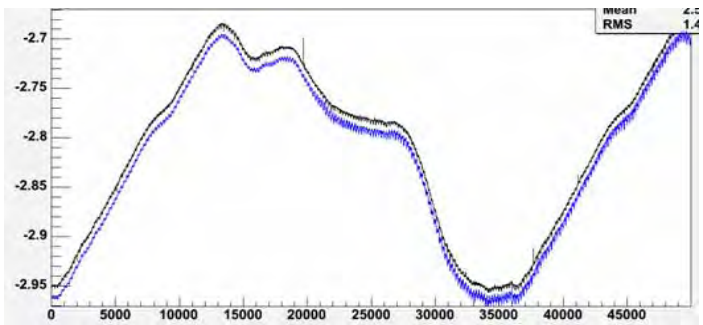


Sequential axial scans



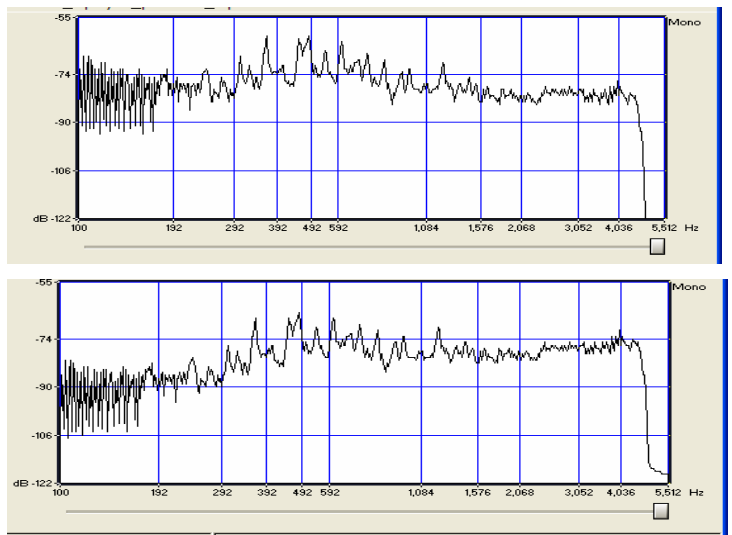
Subtract valleys from ridges to correct for overall shape

(Ridges provide (approx), geometrical reference)

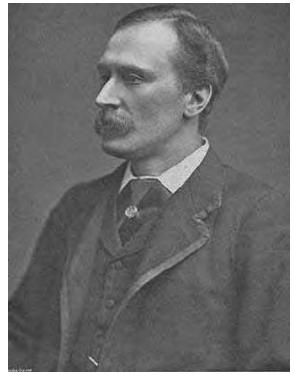


d/dt

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



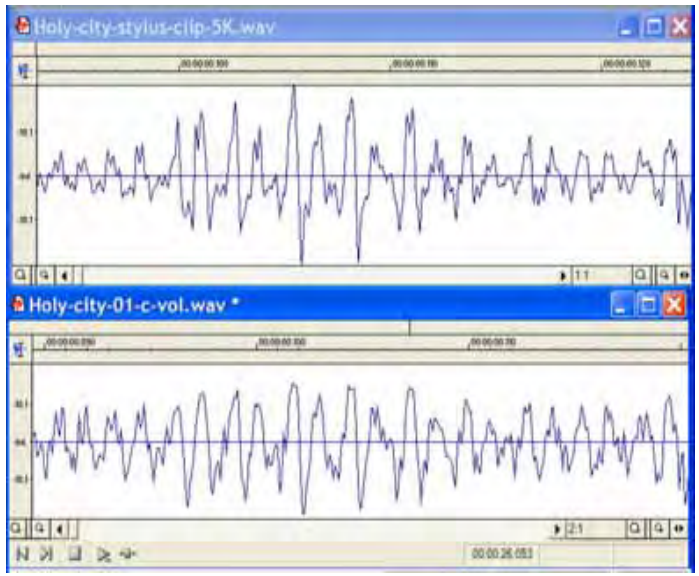
Sound Comparison

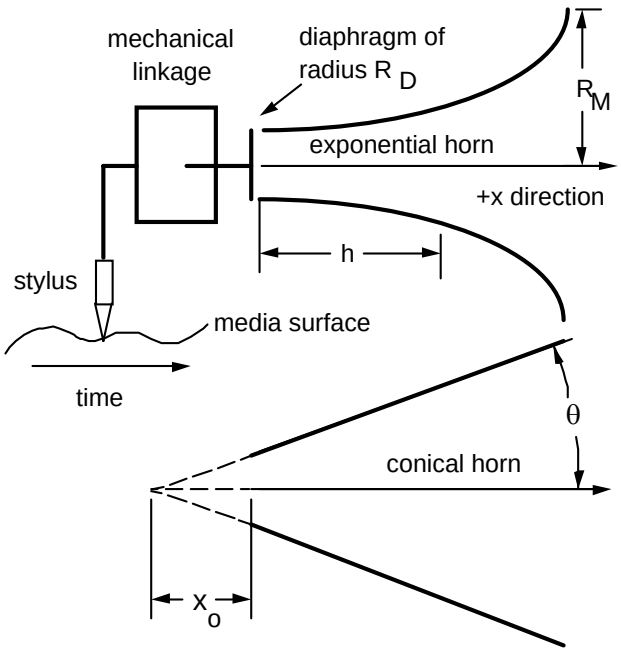


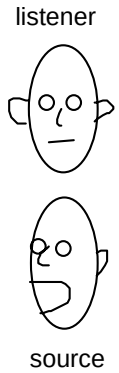
- The Holy City, composed by Stephen Adams,

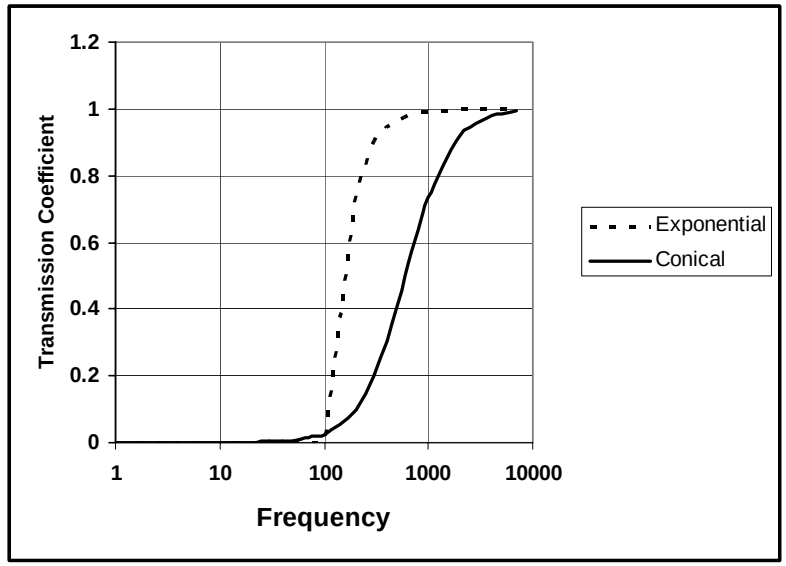
  The Edison and Skedden Mixed Quartet, Amberol 1601

- Stylus
- Optical
- Optical + filter + EQ







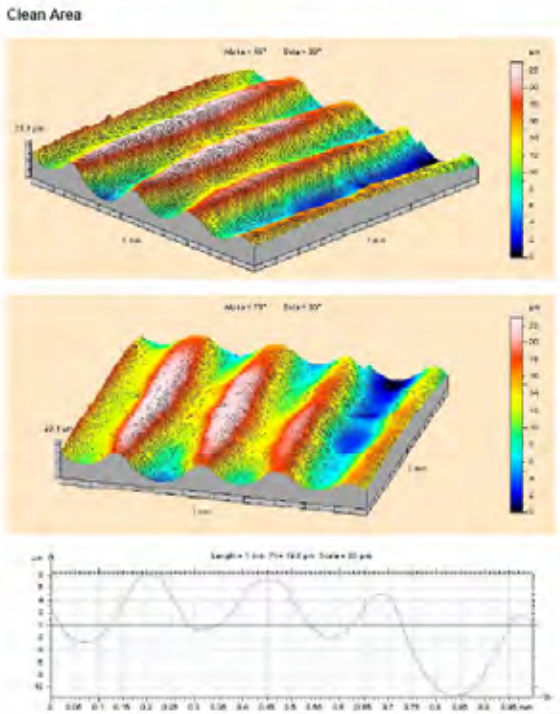


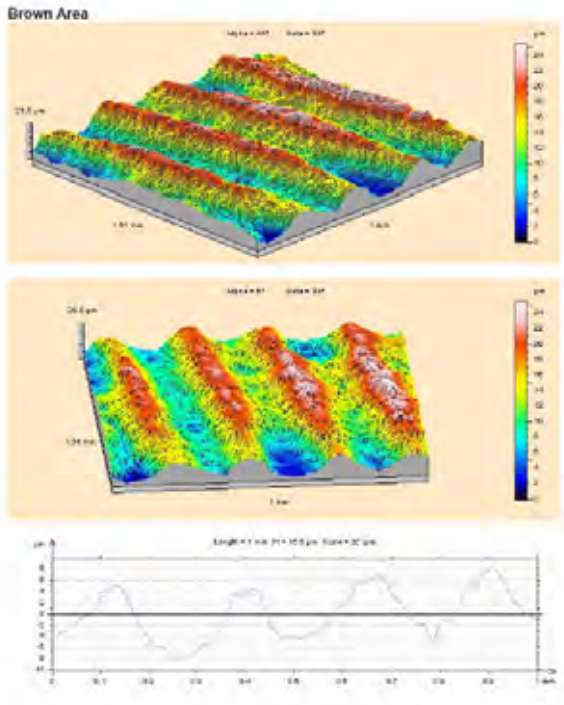
Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.

Damaged or Delicate Cylinders

- Optical restoration of commercial cylinders yields satisfactory results
- Historical value of recorded wax cylinders is greater
  - Earlier recordings
  - Field work
  - Dictation
- Fungus growth and other surface issues can seriously degrade these
- A research priority for the Library of Congress

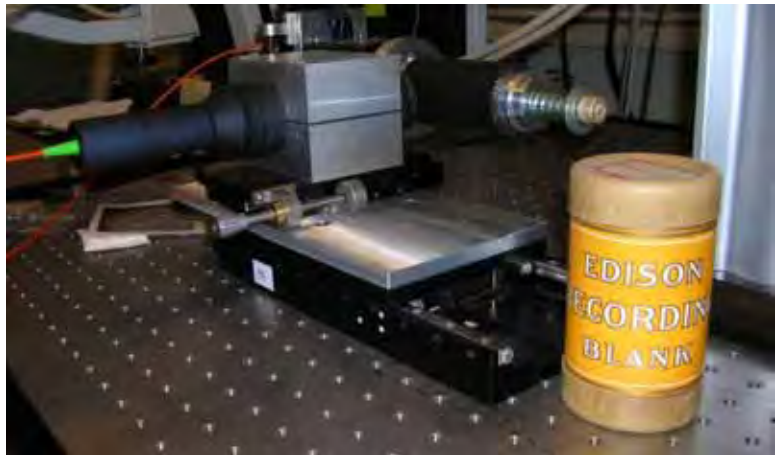
Surface Damage = Sound Degradation

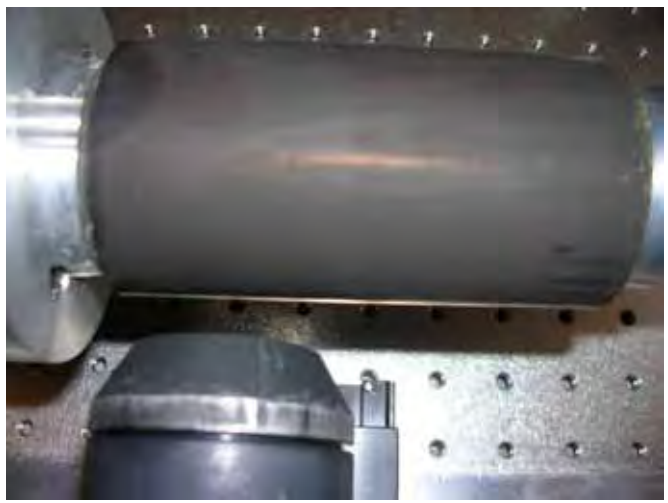




Ethnographic Recordings

Ishi, regarded as the last survivor of the Yahi tribe of No. California was recorded extensively by UC Berkeley Anthropologist Alfred Kroeber (circa 1915). This collection is held at the UCB Phoebe Hearst Museum.





Sam Batwai, Alfred L. Kroeber, and Ishi

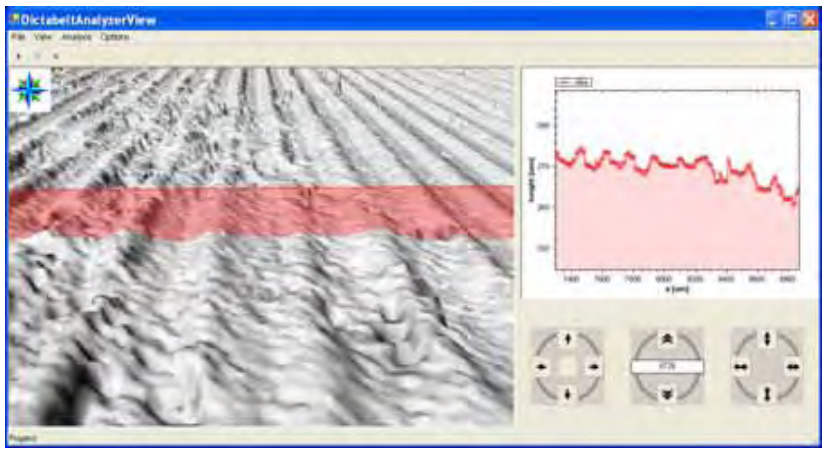
Ishi at Deer Creek

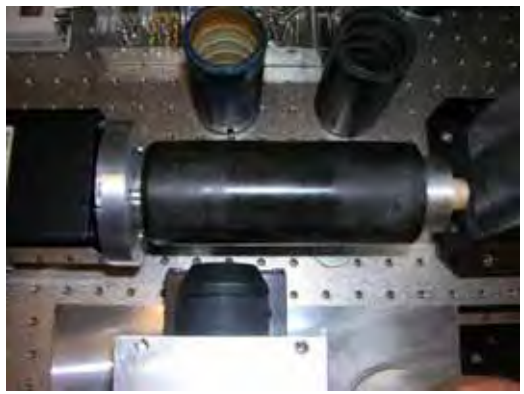
London Wax Cylinders

Jack and Charmian London

JL's Dictaphone machines from the JL State Park

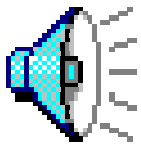
1st cylinder from JL house with mold growth visible





1st Cylinder on 3D scanner

Audio Extraction



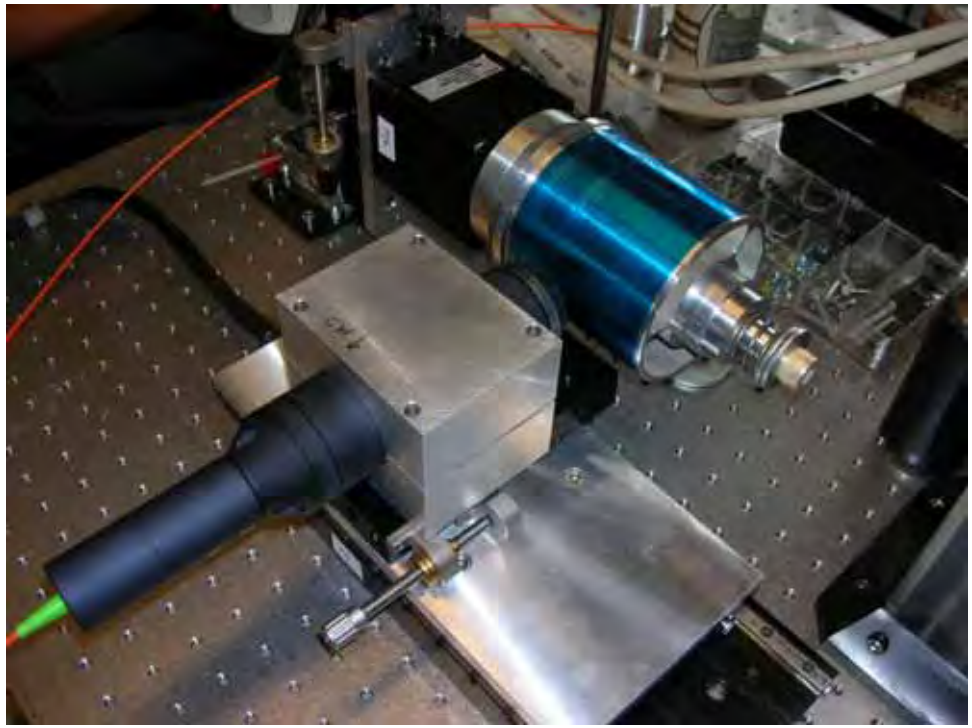
..soon after the affair, very tragically between England and America…
…the Lusitania…
I wish I had time to go and read your
letters…..that it opens up…but I simply cannot.…After the war is over I am intent upon going to England. And then making sure that we shall get together (period)

Voice of Charmian London 1915?

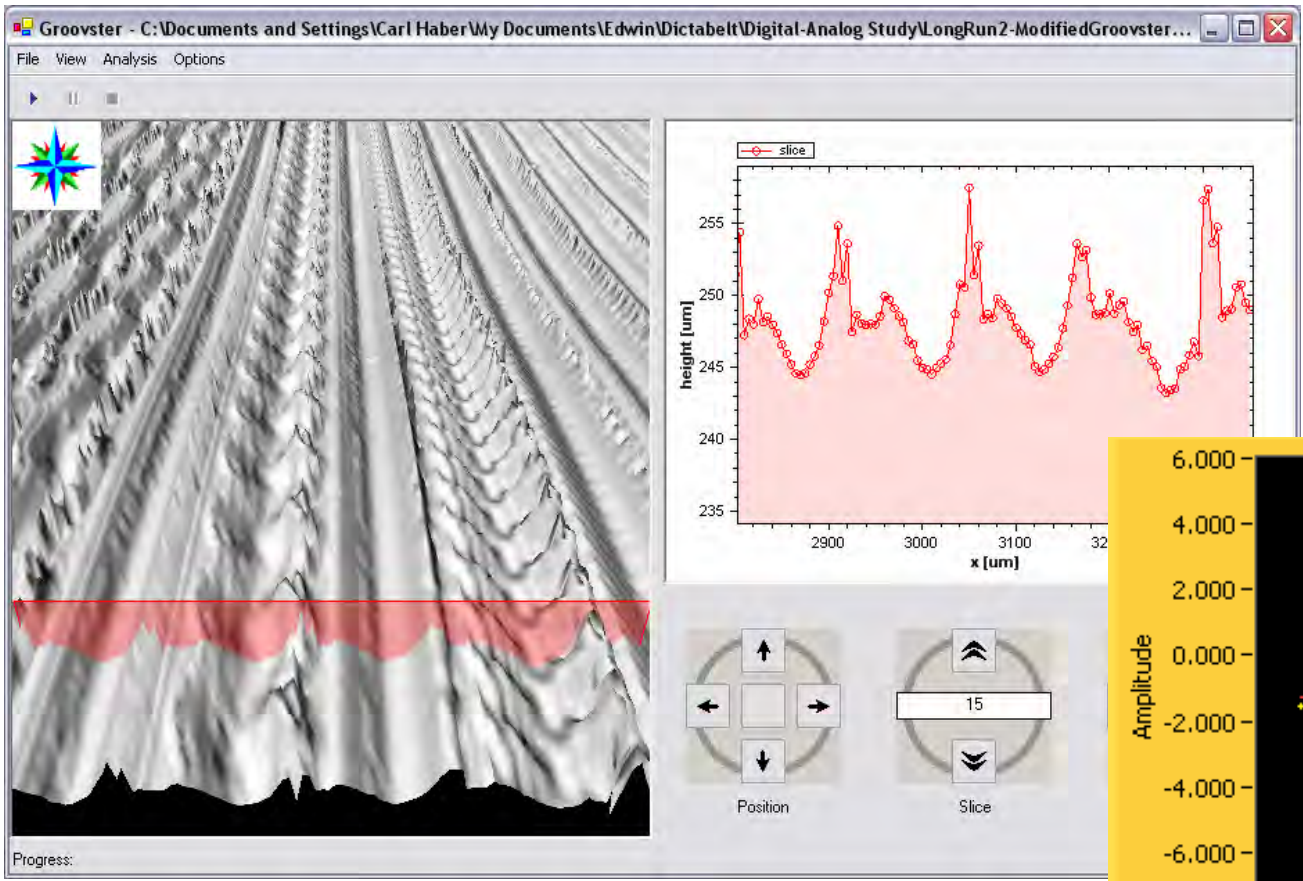
Dictation Belt Scanning

- Plastic dictation belts are historical documents
  - LBJ, JFK presidential phone conversations
  - Dallas PD recording of open mic 11/22/63 (NARA)
- Some belts are worn and cracked
  - NARA proposed a high resolution optical scan as a way to make a digital preservation copy and enable access.
- Scanning tests and analyses have been performed on recorded test belts and other samples.
- Recorded at 42 rpm: long scan times

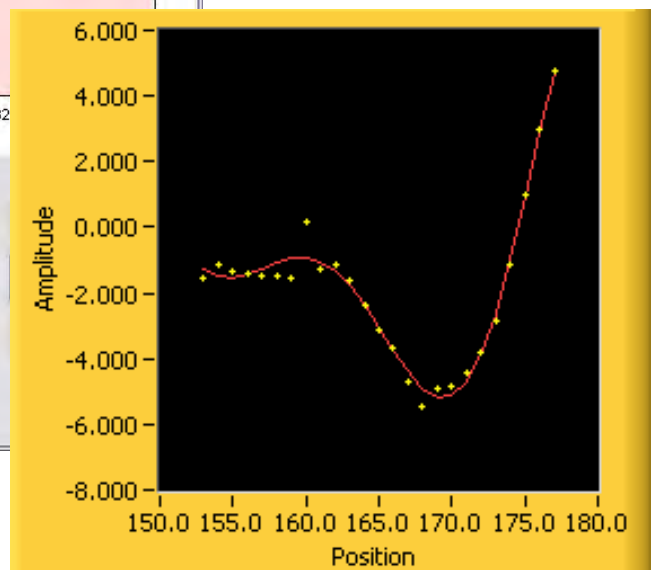

Dictaphone

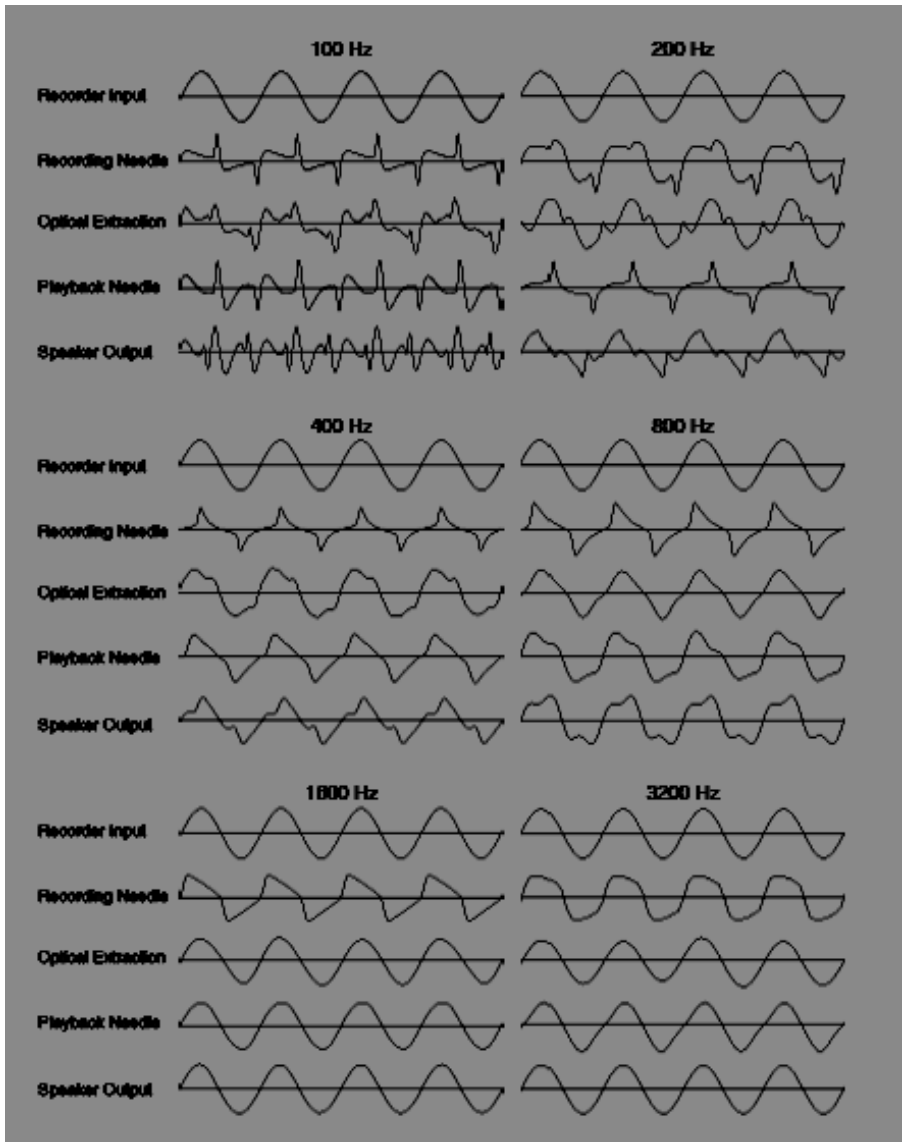


Display of Tone Test Belt

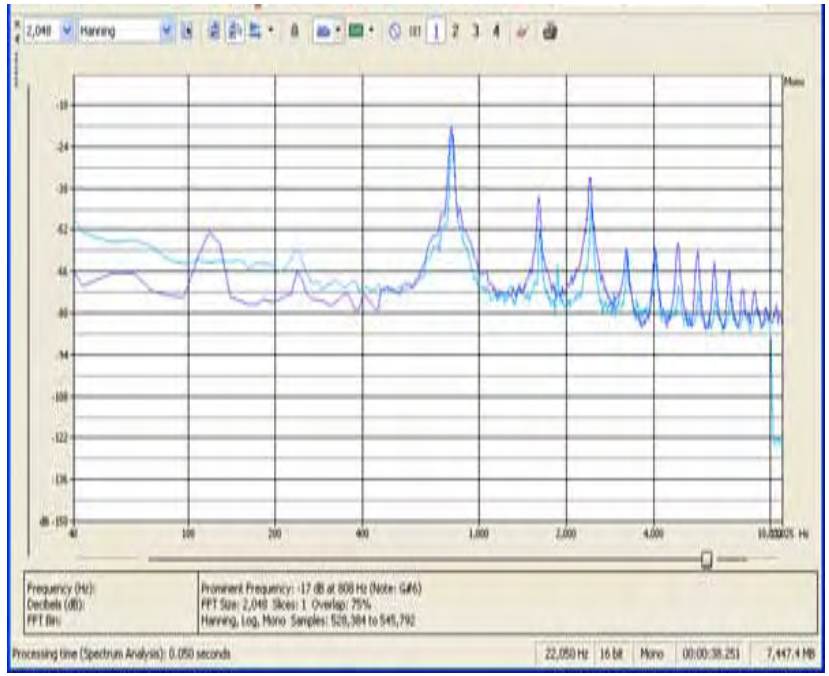


Note complex groove profile

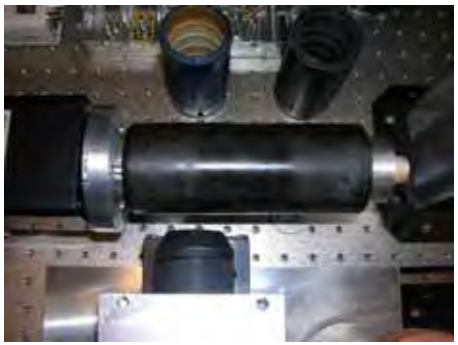


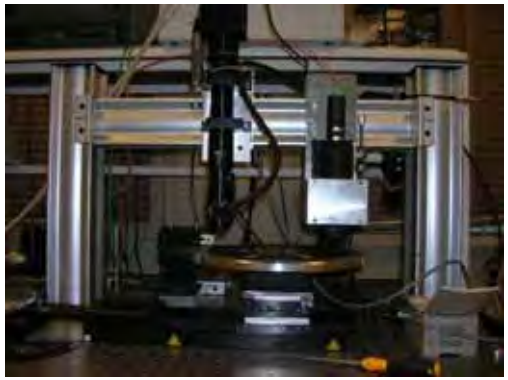


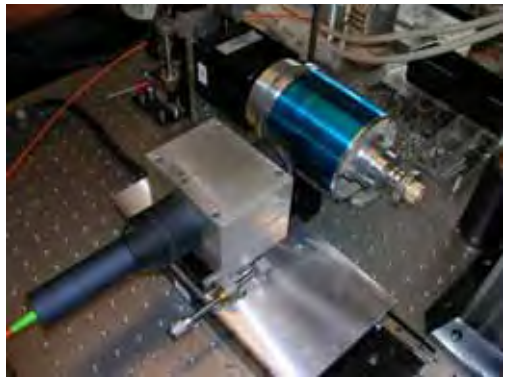
- Considerable non-linearity of the system.
- Bears on validation of process
- Bears on analytical applications

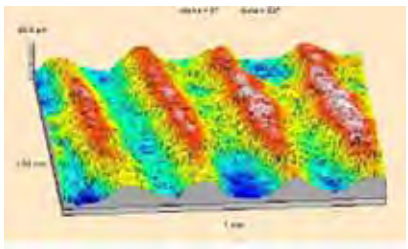


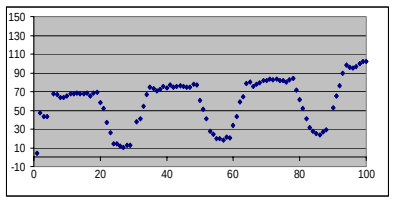
Optical Scanning: A general tool to preserve and create access to recorded sound history

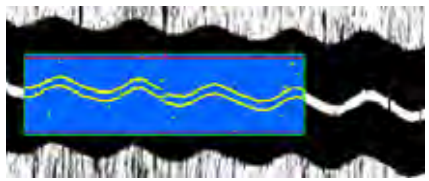












Wax cylinder

Shellac disc

Plastic dictation belt

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

V. Fadeyev and C. Haber **J. Audio Eng. Soc**, vol. 51, no. 12, pp. 1172-1185 (2003 Dec.)
V. Fadeyev et al, **J. Audio Eng. Soc**., vol. 53, no.6, pp.485-508 (2005 June).