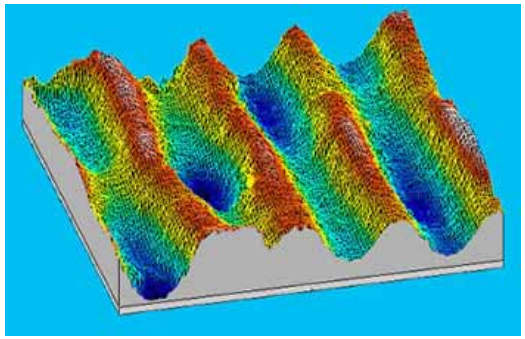

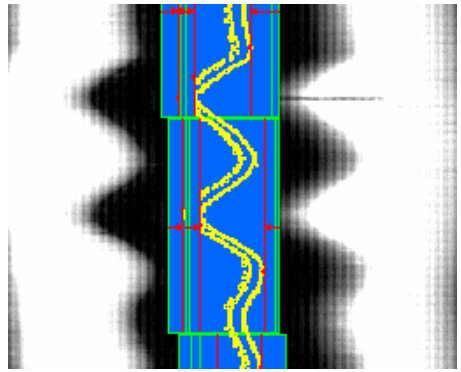

Capturing Recorded Sound Through Imaging:

The IRENE Project and Future Prospects

Carl Haber

Lawrence Berkeley National Lab

Collaboration and Support

Lawrence Berkeley National Lab: CH, Vitaliy Fadeyev, Earl Cornell, Robert Nordmeyer, Jian Jin Chayut Thanapirom, Henry Wang, EdwinWidjonarko, Mitch Golden
Fantasy Studios: George Horn
Library of Congress: Peter Alyea, Larry Appelbaum, Dianne van der Reyden, Elmer Eusman, Nels Olson

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University of Southampton UK
EIF- Fribourg, Switzerland

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

America's Collections

Fig. 4.1 U.S. Institutions Have Taken Responsibility to Preserve 4.8 Billion Collections Items	
Books/Bound Volumes	1.7 billion
Microfilm/Microfiche	1 billion
Natural Science Specimens	820.2 million
Photographic Collections	727.4 million
Archaeological Collections, individually cataloged	197.8 million
Unbound Sheets, cataloged in items	95.8 million
Online Files	54.6 million
Historic Objects	48.3 million
Recorded Sound	46.4 million
Unbound Sheets, cataloged in linear feet	43.6 million
Moving Images	40.2 million
Art Objects	21.2 million
Digital Materials	9 million
Archaeological Collections, cataloged in cubic feet	2.6 million

Heritage Health Index 2005

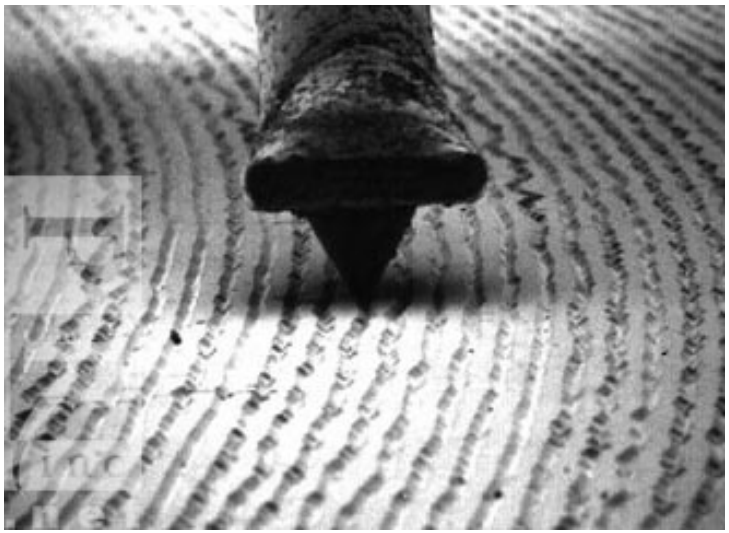
- US museums, libraries, and other institutions collectively hold 4.8 Billion items
- 46.4 million sound recordings
  - 14% are in need of preservation (6.5 million)
  - But 42% are in unknown condition (19.5 million)
  - And there is also the rest of the world
- Archivists want to reformat all pre-digital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

Digitization

Automatic book scanner

- Robotic scanning of texts and optical character recognition (OCR) are now in wide use at major libraries, Google?…
- Unlike texts, digitization of historical sound recordings is often an invasive process-by definition

Traditional Contact Playback



Bulky stylus riding in a narrow groove => Issues with

- tracking
- condition of the groove
    - debris and contamination
    - wear

Transcription process: requires trained manpower or supervision.

Maintenance of legacy playback systems

History

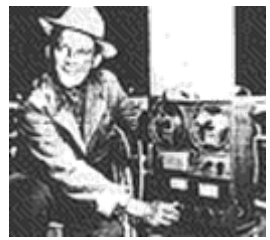
- 1859 Leon Scott: *Phonoautograph* paper recorder
- 1877 Thomas Edison invents sound reproduction on tin foil *Phonograph*

- 1885 Bell and Tainter introduce wax cylinder
- 1887 Emile Berliner invents disc *Gramophone*
- 1925 Western Electric *Orthophonic* (electrical) system

end of the "**Acoustic Era**"

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

- 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

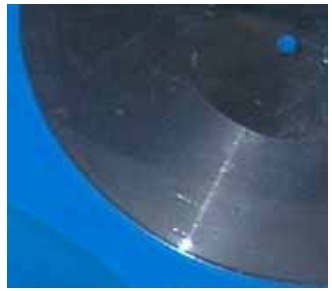
- 1963 Cassette magnetic tapes
- 1982 Compact Disc (*CD*)

end of the "**Analog Era**"

- 2001 Apple *IPOD*

Sound Carrier Degradation

Fungus
Wax bloom



oxidation

flaking

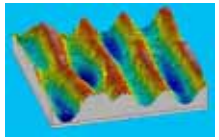
exudation

breakage

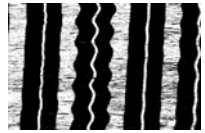
dirt

warpage

- At Berkeley we are developing methods of optically recovering mechanical sound recordings **without contact** to the medium – like text scanning
- Address concerns of the preservation, archival, and research communities:
  - Preservation: Restore or stabilize delicate or damaged media
  - Access: Mass digitization of diverse media
- The approach evolved naturally out of methods of optical metrology, pattern recognition, and image processing in use for physics research.
- First presented at the Library of Congress in 2003



Non-Contact Digital Imaging



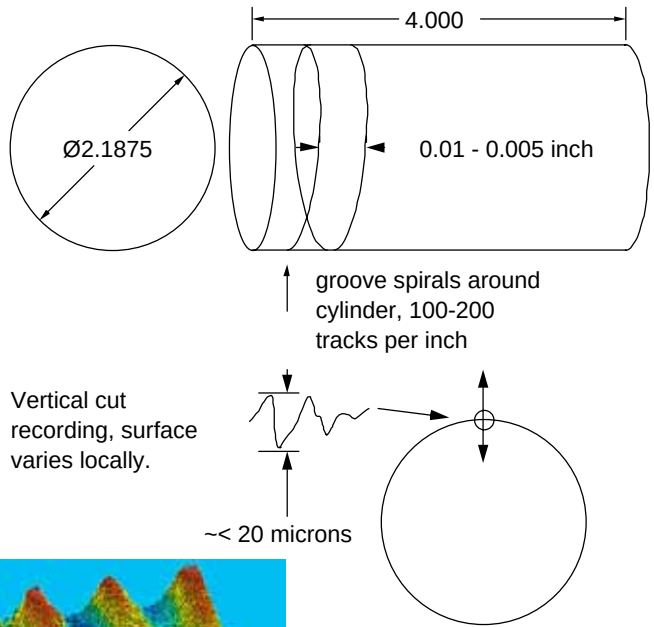
- Create a high resolution digital map of entire surface
- Computer plays record (image) with a virtual stylus
- Product
  - Standard digital sound files (ie .wav)
  - High resolution digital images which may be reanalyzed later as well
- Protects samples from further damage
- Repair existing damage through “touch-up”
- Reconstruct broken records
- Offload aspects of restoration to automated software

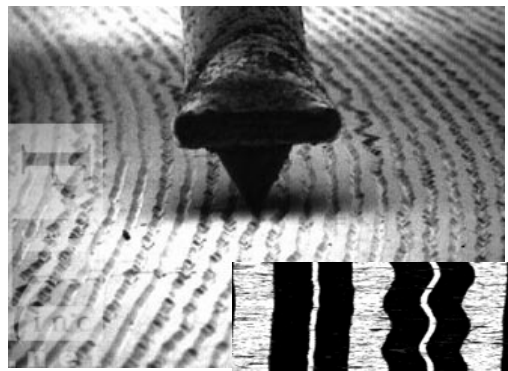
A “smart” copying machine for records

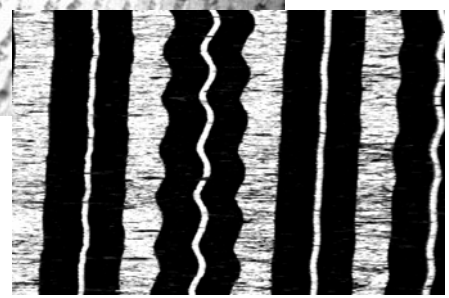
Mechanical Recording Principles

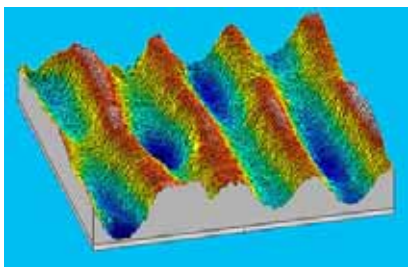
Cylinder: groove varies in depth (Vertical Cut)

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

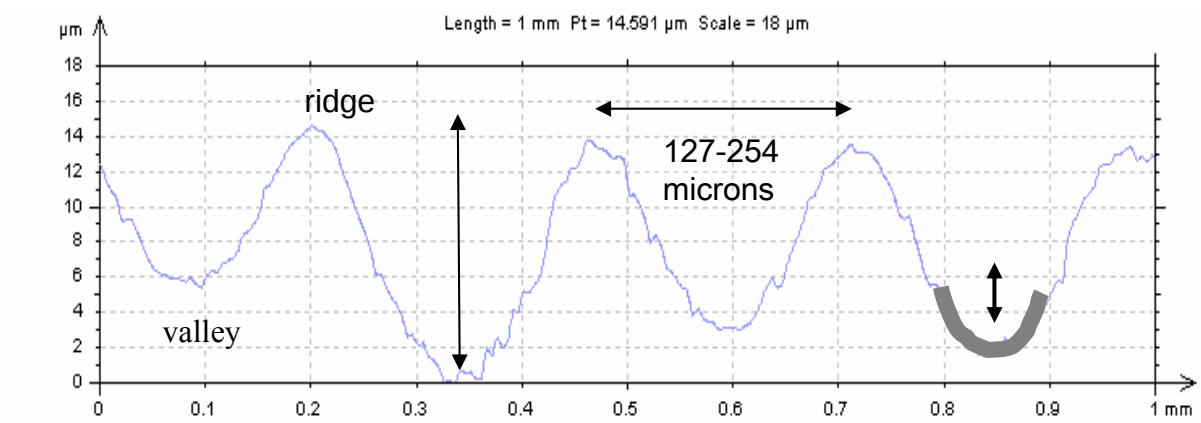




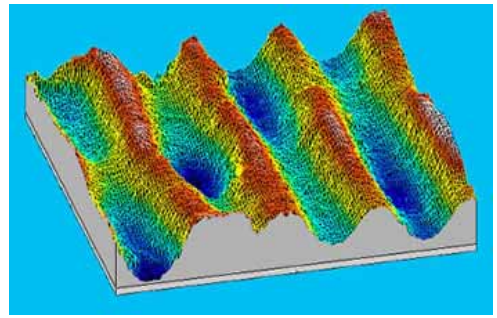




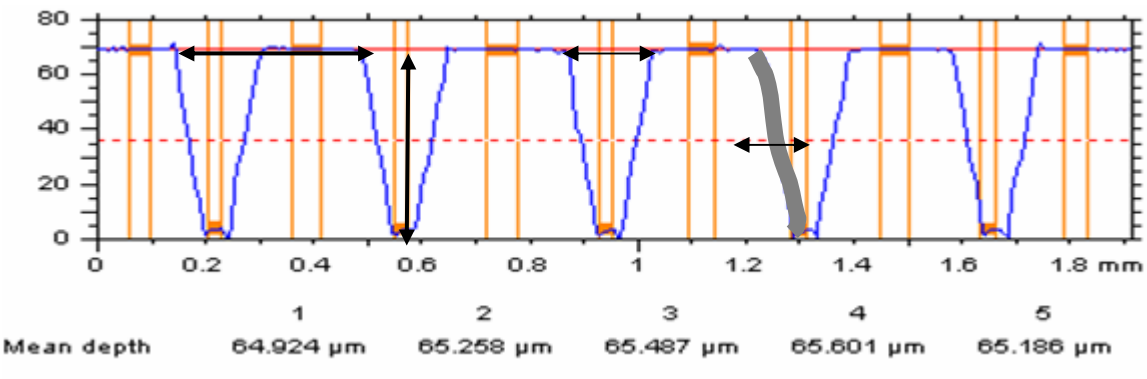
Audio is encoded in micron scale features which are >100 meters long



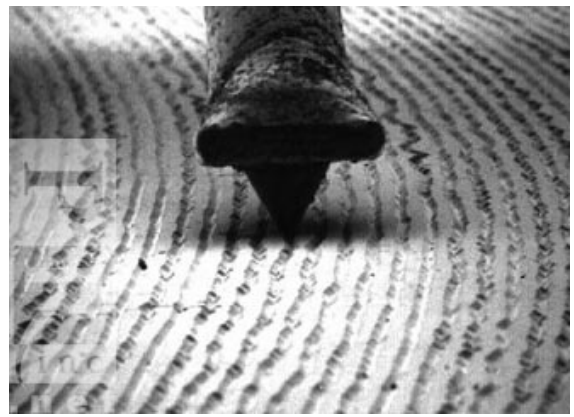
Cylinder surface



400 µm 150 µm



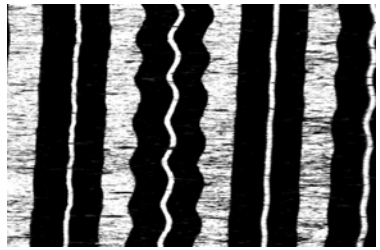
Disc surface



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

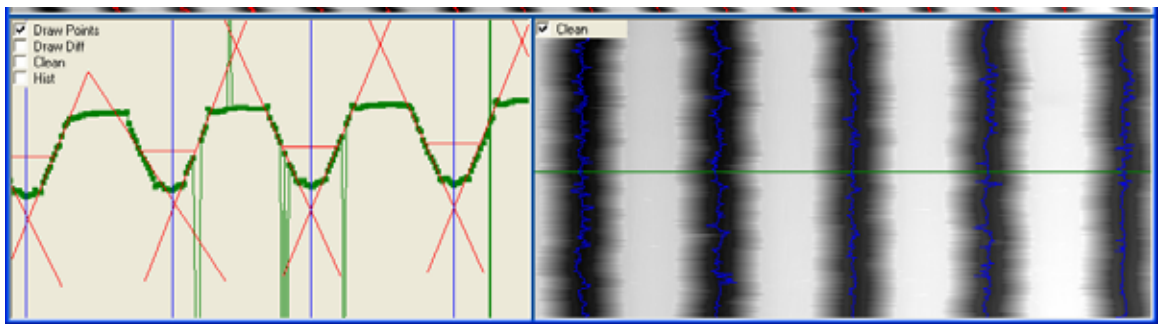
2 and 3 Dimensional Images

Intensity

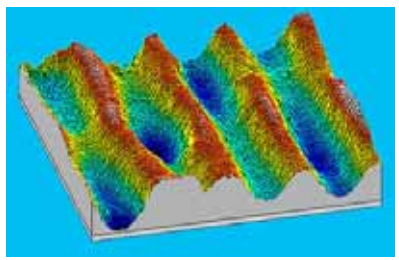


Micro-photograph of shellac disc:
A two dimensional image "2D"
can measure <u>lateral</u> grooves

Height



Surface profile of disc.
A 3D image is a more
detailed measurement

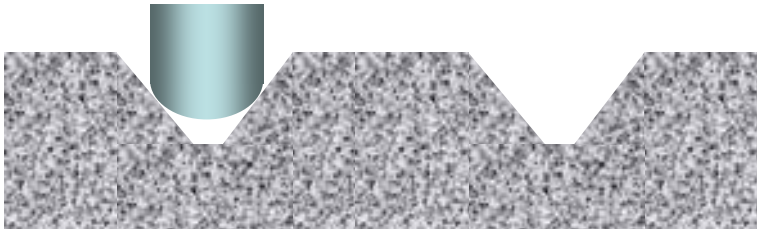


Surface profile of a wax cylinder:
A three dimensional image "3D"
is <u>required for vertical</u> cut grooves

Redundancy

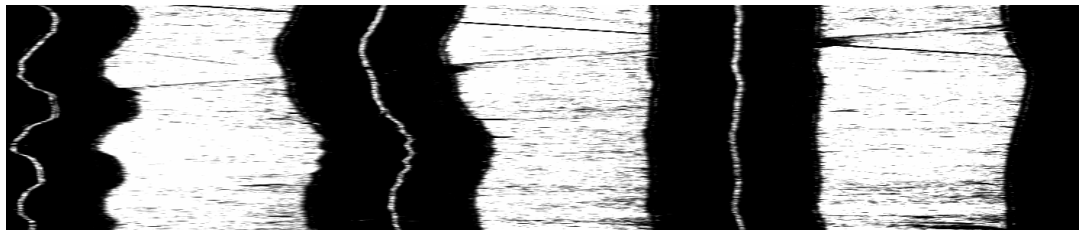
Audio stored in entire profile

Stylus



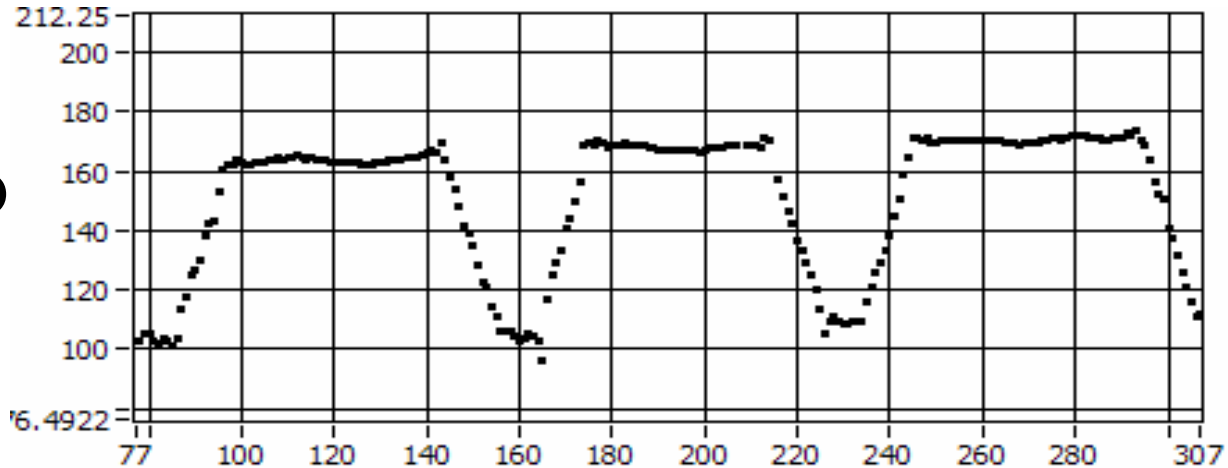
Stylus comes into contact at 2 points

2D



Measure the groove bottom with 2 points/slice

3D

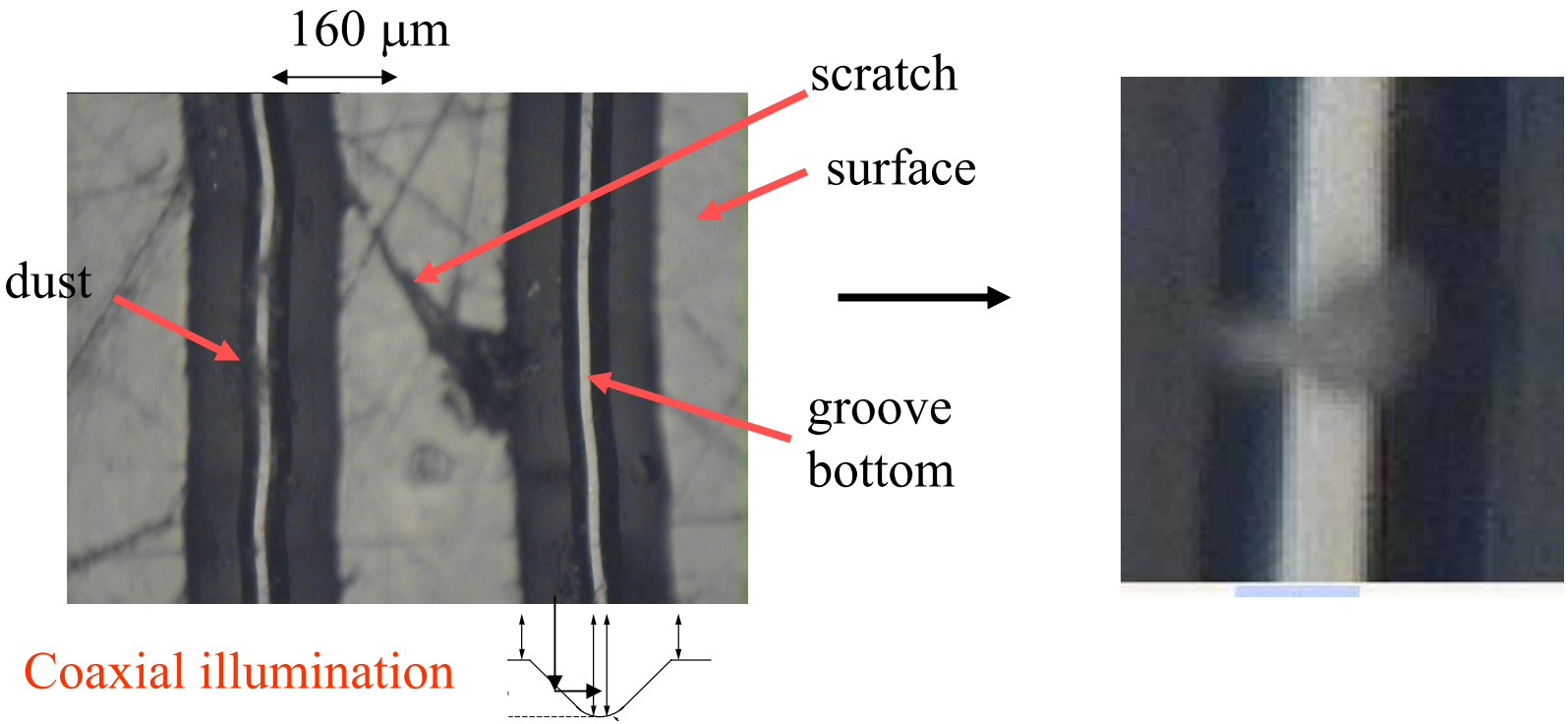


Measure the entire groove with ~30 points/slice

The Method

- Digitally image the surface
- Cover with sequential views or grid.
- Stitched together: surface map
- Process image to remove defects
- Analyze shape to model stylus motion.
- Sample at standard frequency
- Convert to digital sound format.
- Real time playback is not required
- Store results as standard digital sound files (.wav) and high resolution digital images

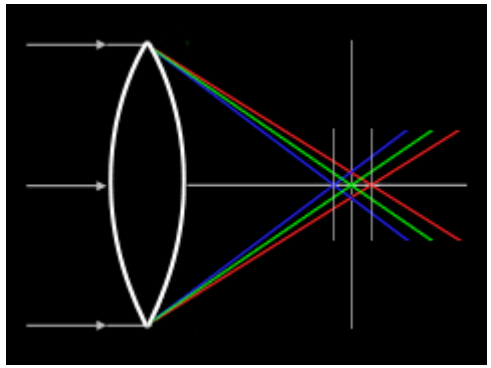
2D Imaging: Electronic Camera

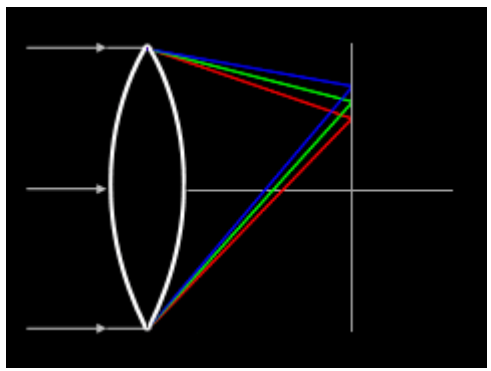


Coaxial illumination

- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface
- High speed cameras allow near “real-time” imaging
- Generate 4-8 GB per disc raw, 300 MB processed image data per 10” side

3D Imaging: Chromatic Aberration

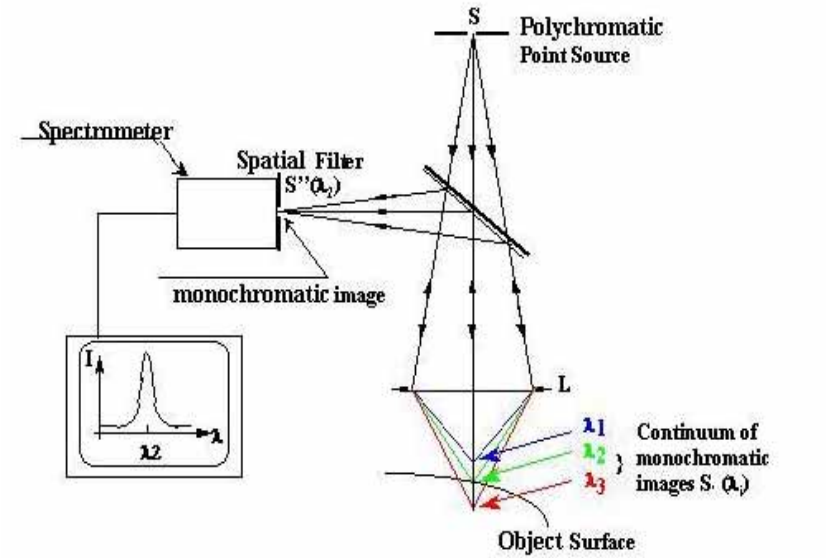




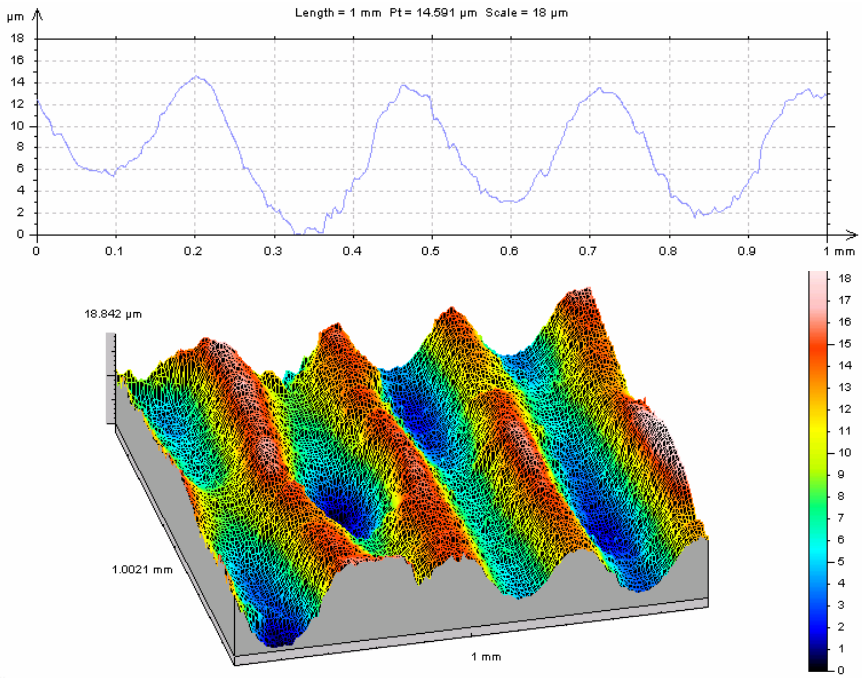
3D Imaging: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.

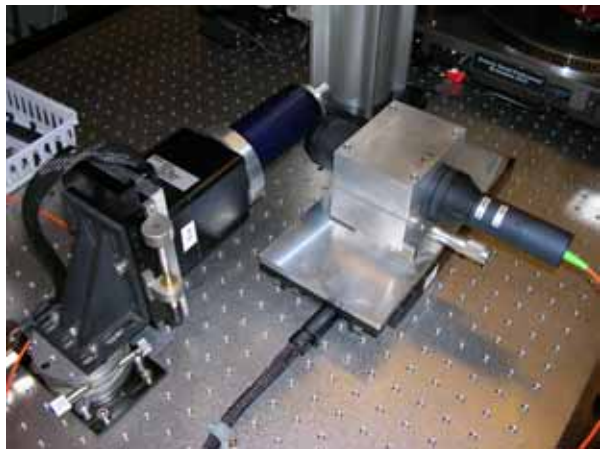
Point by point scan



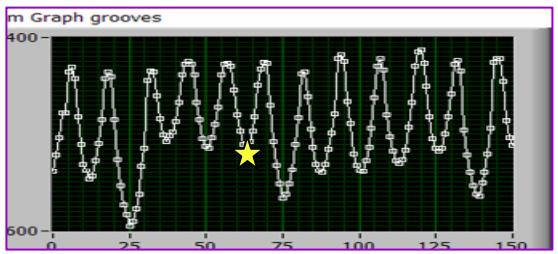
Surface of an Edison cylinder



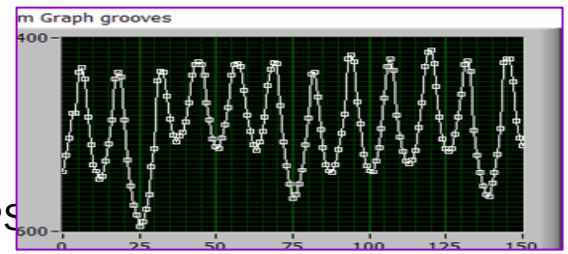
New Probe Technology



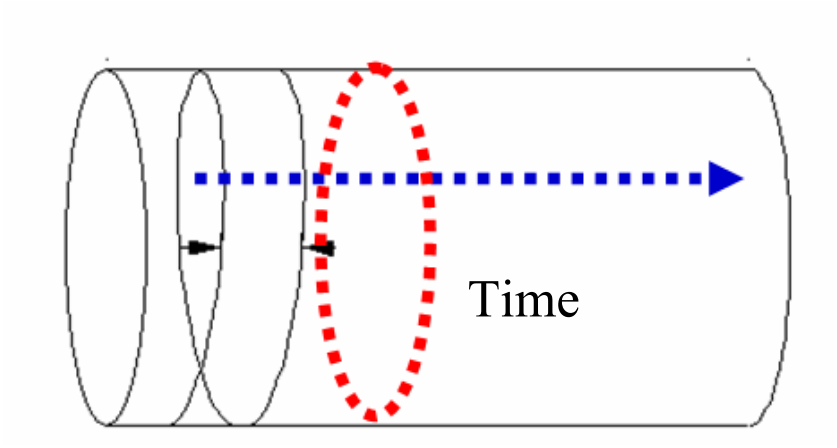
Measures 1 point at
1000 – 2000 per second

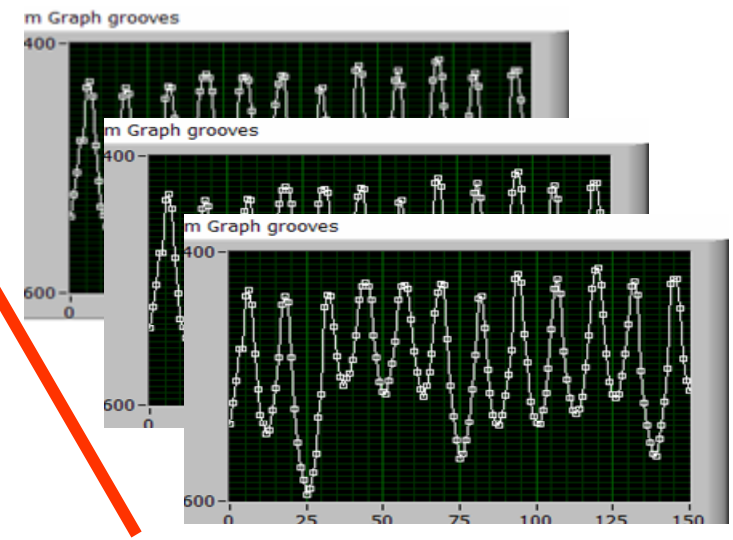


Measures 180 point simultaneously on 10 micron grid at up to 1800 per second



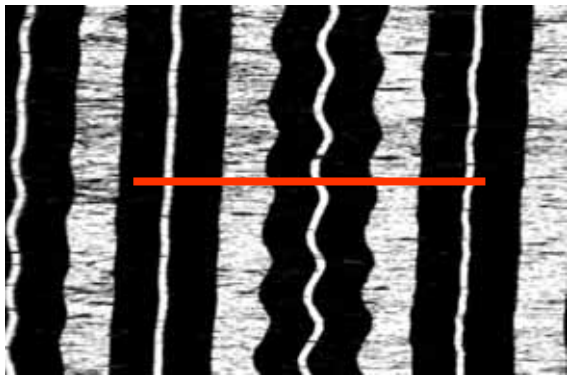
Speed and Data

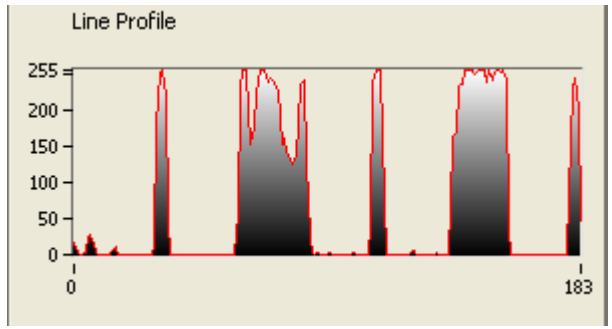


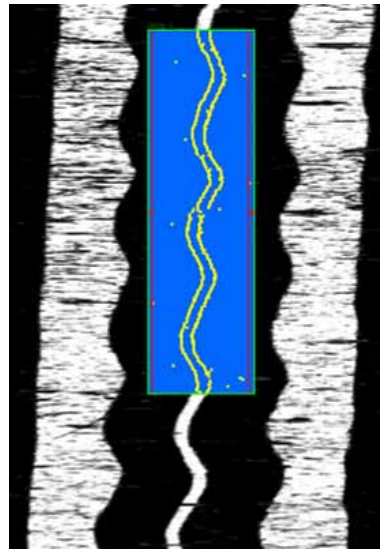


- Point by point measurement
- Exposure time per point
- Grid along time direction (red) = digital sampling
  - 0.02 degree = 18,000 samples = 48 KHz
- Grid along axis direction (blue) = points per profile
  - Typically 5 – 10 microns
- 1 probe: ~ 80 hours for 2-4 minutes of audio
- 180 probes: ~ 20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

Image Analysis (2D case)



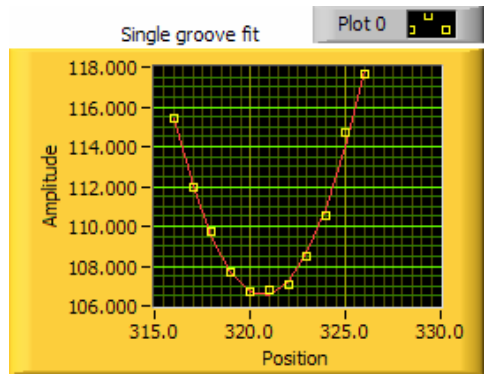




Feature extraction and measurement

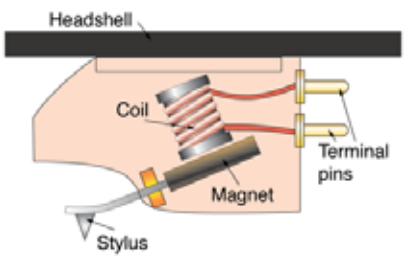
Measured width of features provide a natural noise detection and removal tool.

3D images are analyzed in an analogous fashion



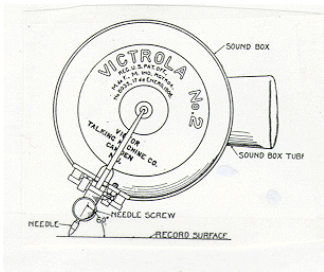
What is the relationship between "groove" and sound?

Electro-magnetic case

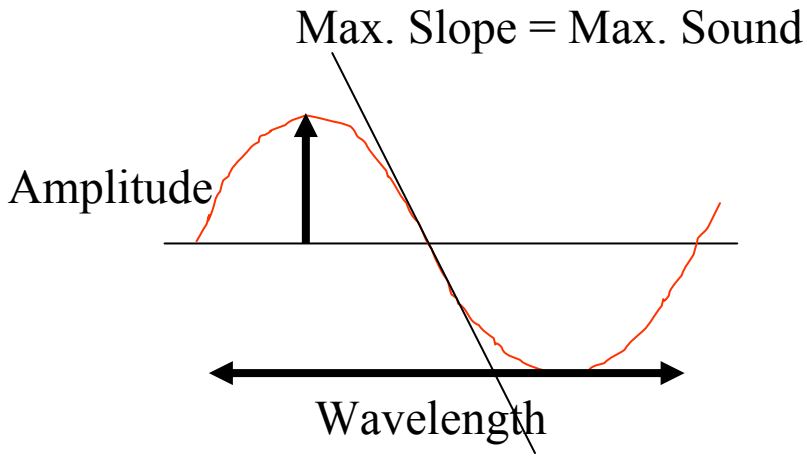


induction

Acoustic case



Diaphragm is over-damped to provide flat response



Sound = Stylus Velocity

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

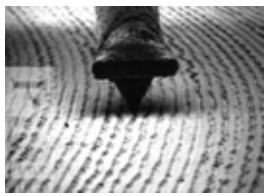
("constant velocity condition")

Signal Recording and Reproduction

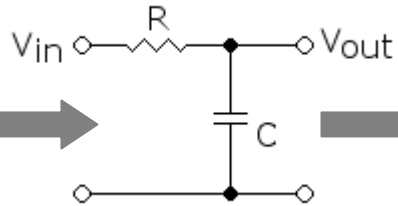
- Frequency: flat response over accessible range
- Amplitude: linear response to maximum value

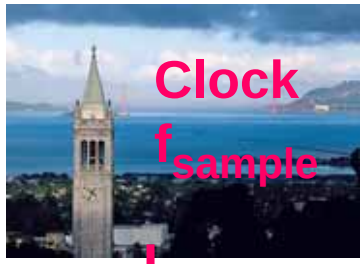
- Analog: amplitude & time are stored in analogy as a continuous or randomly distributed variable
  - Phonograph record: amplitude=stylus velocity, time=position on the spiral groove
- Digital: amplitude and time are discrete
  - WAV file: amplitude=bits, time=sample#
- Mixed
  - Film: amplitude=grain size and distribution, time=frames

Analog waveform

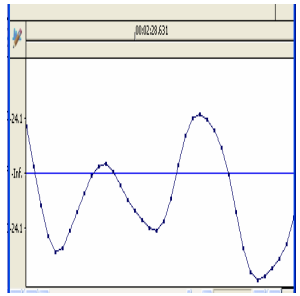


Low-pass filter
$f_0 < f_{sample}/2$

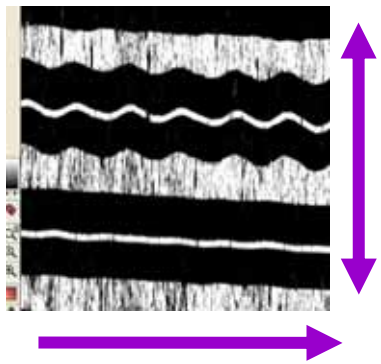




ADC



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



Pixel: 100-400 KHz

Comparison

- ✘ Data intensive
- ✘ Cost
- ✘ Scanning speed
- ✘ Is fidelity sufficient?
- ✘ Powerful restoration methods for audio already available

- ♪ Non-contact
- ♪ Robust – wax, metal, shellac, acetates…
- ♪ Effects of damage and debris reduced by image processing and geometry
- ♪ Re-assemble broken media
- ♪ Resolve noise in the "spatial domain" where it originates.
- ♪ Effects of skips are reduced or eliminated.
- ♪ Distortions (wow, tracking errors, etc) absent or geometrical corrections.
- ♪ Operator intervention during transcription is reduced, mass digitization.
- ♪ Produce standard audio output data format (.wav)
- ♪ Can archive images for future re-analysis with new algorithms.

Original Test 2002

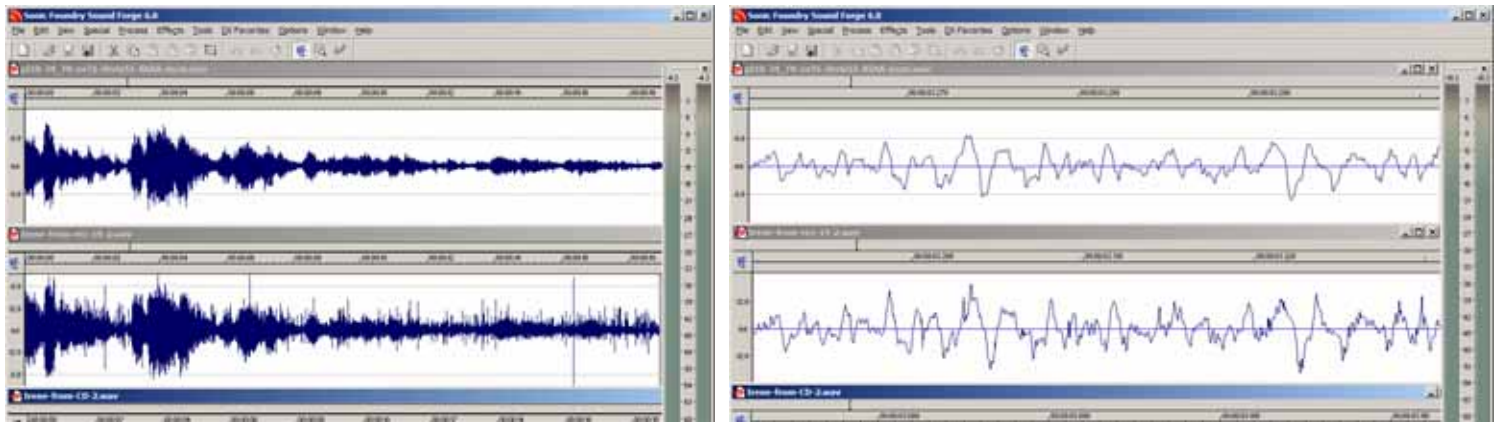
Used a commercial 2D optical measurement system

<u>Required 40 minutes to scan 1 second of audio</u>

19.1 seconds | 40 ms

optical

stylus



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

- Clear reduction in "clicks and pops"
- Similarity of fine waveform structure

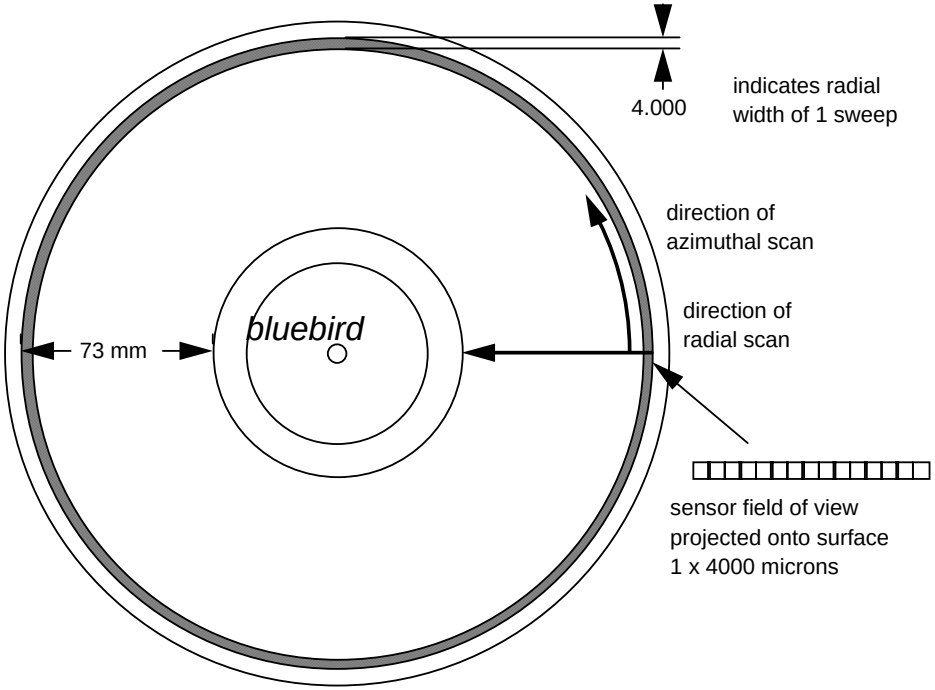
Projects

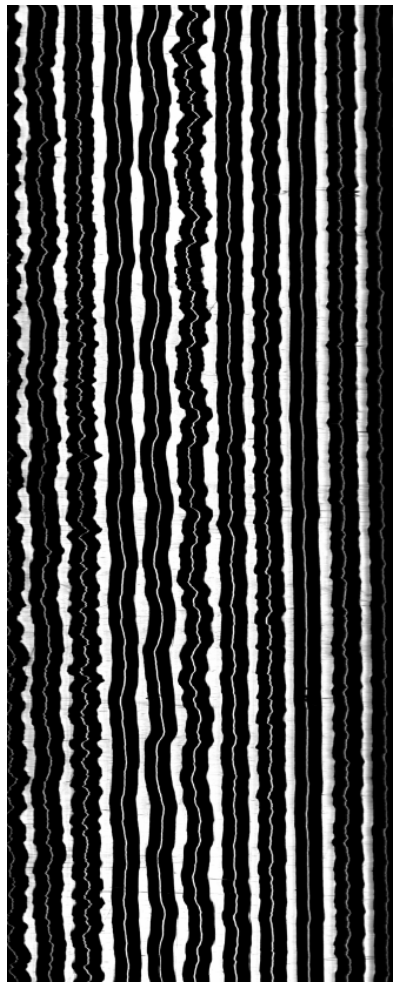
- This led to interest and support from the Library of Congress and others.
- Can you speed this up?
  - IRENE: a fast 2D optical scanner for disc records
  - Digital access to the most common media + special formats
  - Installed at the Library of Congress 8/2006
- What is the gain with 3D?
  - R&D scans on “Edison” cylinders and other media
  - Preservation and restoration of early and damaged recordings
  - Feasibility study for preservation transfers of dictation belts
  - Propose to build a 3D machine

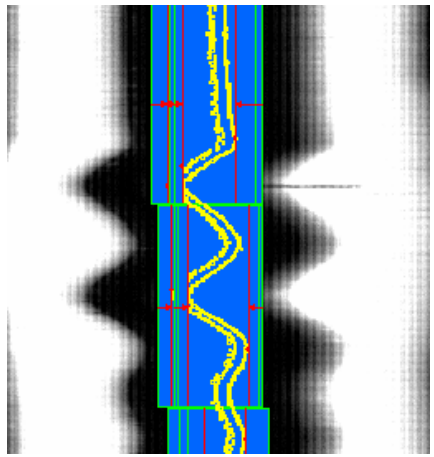
2D Scanner: Goals and Features

- Access and assessment of discs, preserve otherwise unplayable items
- Understand limits and capabilities of this approach
  - Noise, Frequency response, Linearity, Sampling
- 2D imaging of groove bottom and/or top.
- Emphasize throughput: scan 3 min record in 10-15 minutes
- Encompass as much variation in media as possible.
- Handle broken discs.
- Facility to (temporarily) flatten flexible media (Memovox)
- User friendly interface.
- Commercial off-the-shelf components.
- Provide a test bed for the mass digitization application.
- Provide detailed statistical information about media condition.
- Do no harm.

Line Scanning: disc is in motion







- 4000 pixels@~5x10^3 lines/s
- Requires bright illumination
- 7.6 x 10^5 lines/outer ring
  - **390 KHz max sampling**
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.

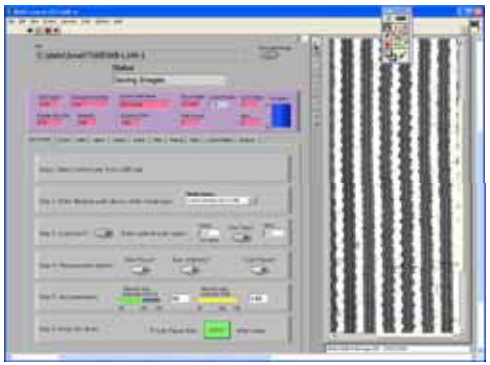
Key Technical Issues

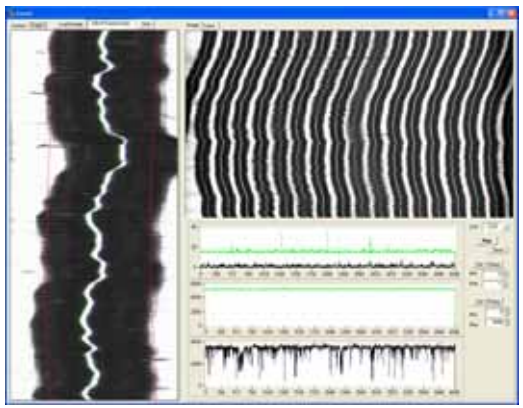
- Fast camera
- Illumination
  - Intensity
  - Stability
  - Heat
- Wide field of view optics
- Active focusing system
- Vibration Control
- Motion Control
- Image capture and processing

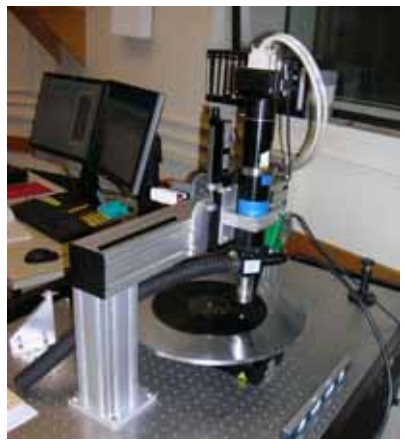
I.R.E.N.E.

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, 1 year evaluation

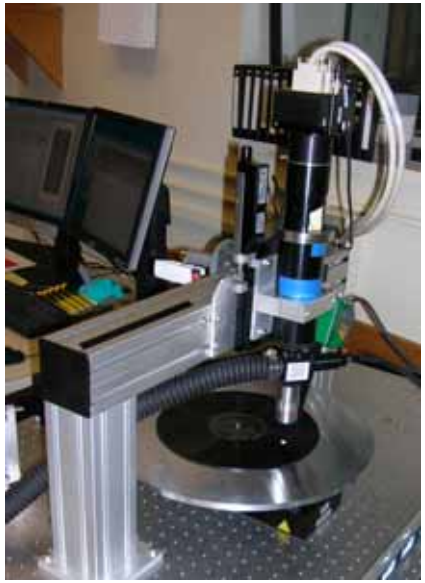


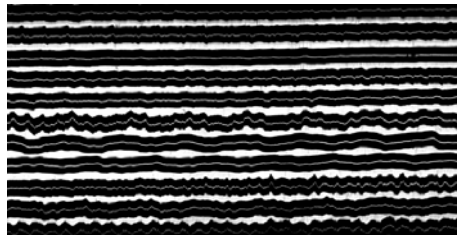




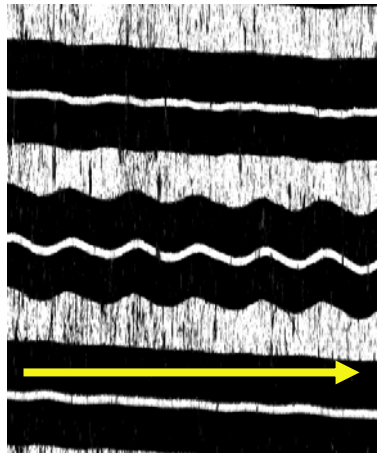
Advisory Panel

- Representation from technical or audio experts
  - Adrian Cosentini (NY Philharmonic)
  - Vitaliy Fadeyev (LBNL)
  - George Horn (Fantasy Studios)
- Representation from "user community"
  - Sam Brylawski (UCSB)
  - Jake Horniak (Smithsonian)
  - Mark Roosa (Pepperdine)
  - Anthony Seeger (UCLA)
  - Abby Smith (independent)
  - Sarah Stauderman (Smithsonian)

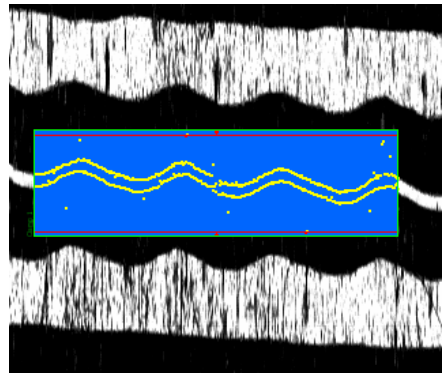




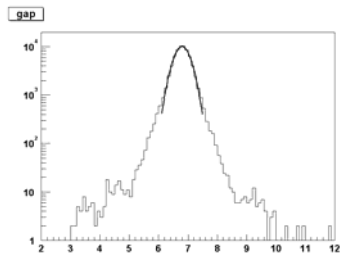
Line scan



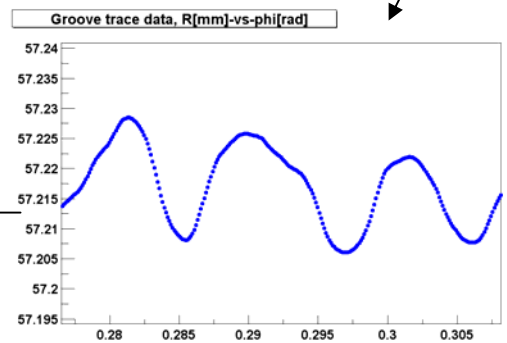
Time
Pixels = 104 KHz

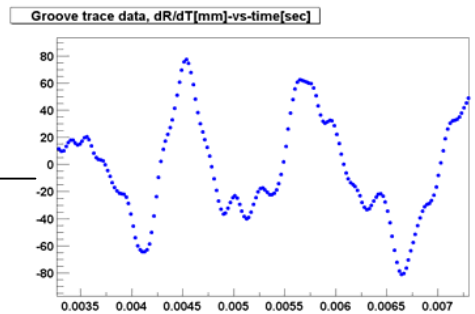


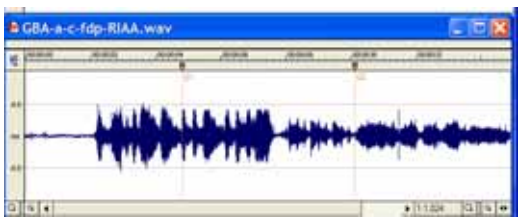
Width across
groove bottom



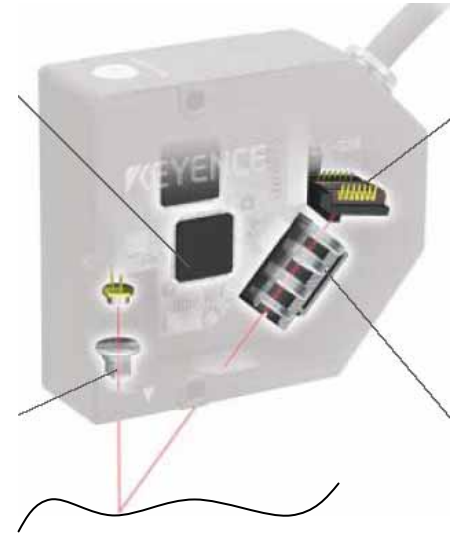
Measure slope
at each point
(stylus velocity)

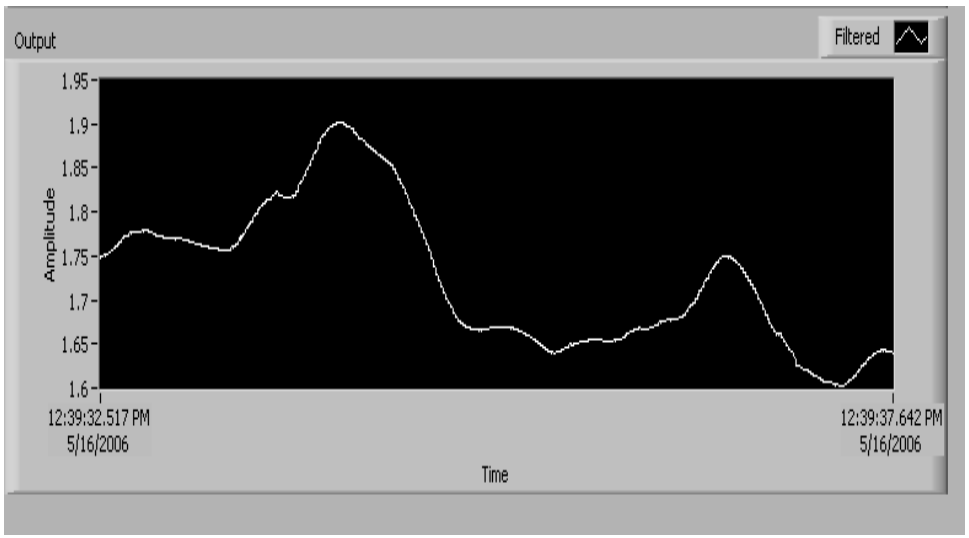






Average
Filter using width cut

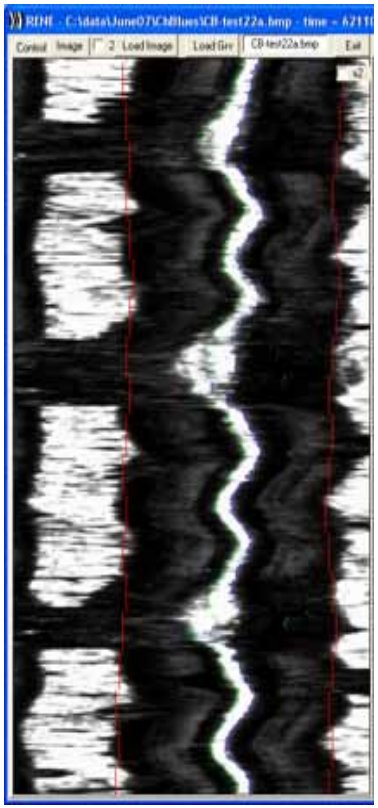




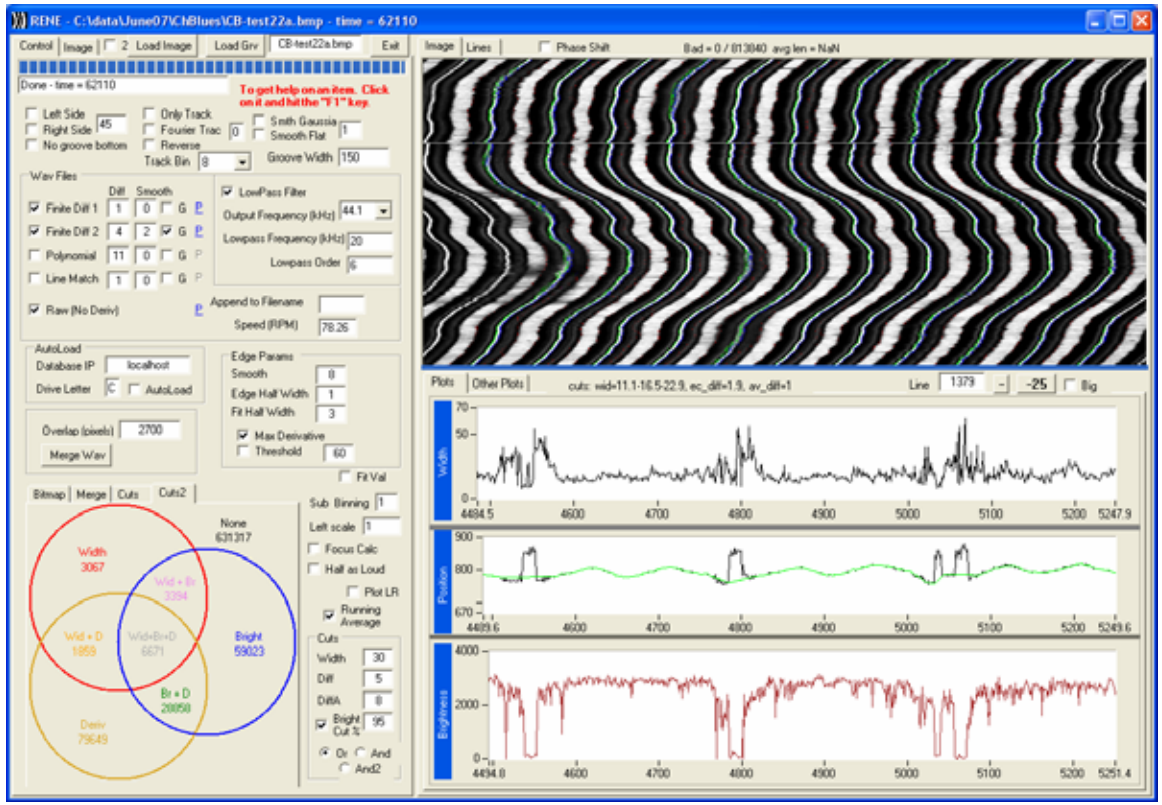
Measured profile of record warpage used to actively correct scanner focus.

Example of IRENE Analysis

Image View



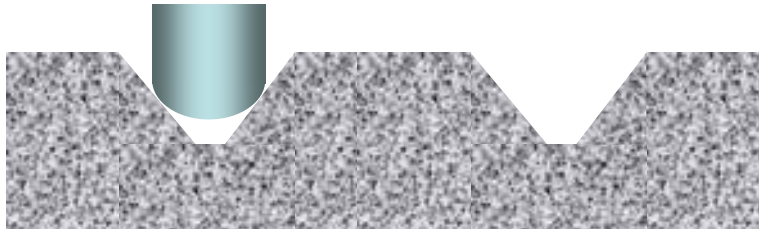
Control View



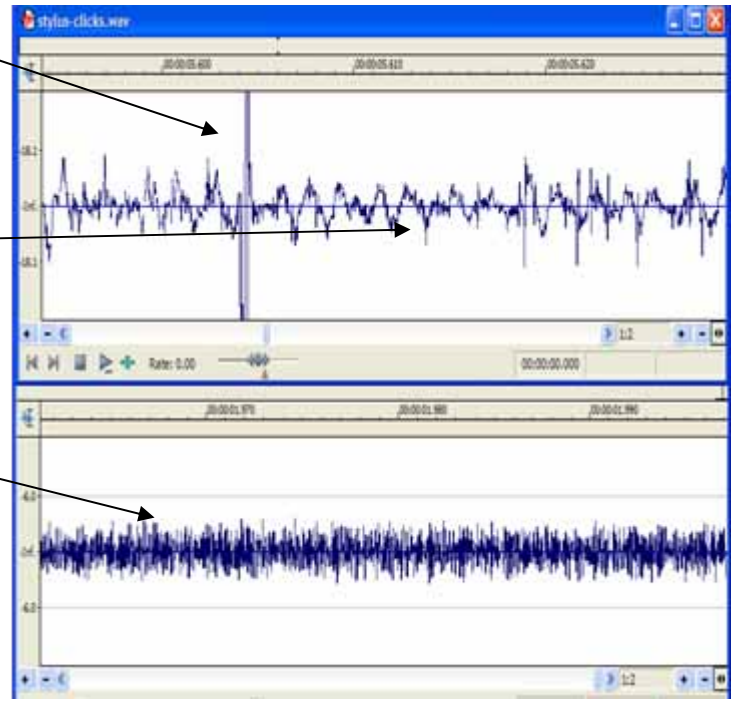
Performance Issues

- Data taking
- Robustness
- Noise reduction
- Noise floor
- Frequency response

Sources of Noise



- Noise = random fluctuations in a signal
- Characterized by
  - Origin
  - Time structure, Amplitude
- Impulse noise (clicks) (stylus playback)
  - Due to: scratches, debris
  - Rare, large amplitude
- Crackle (stylus playback)
  - Due to: stylus wear
  - Frequent, moderate amplitude
- Broad band noise (hiss) (simulated)
  - Due to: fine texture of surface
  - All frequencies, small amplitude

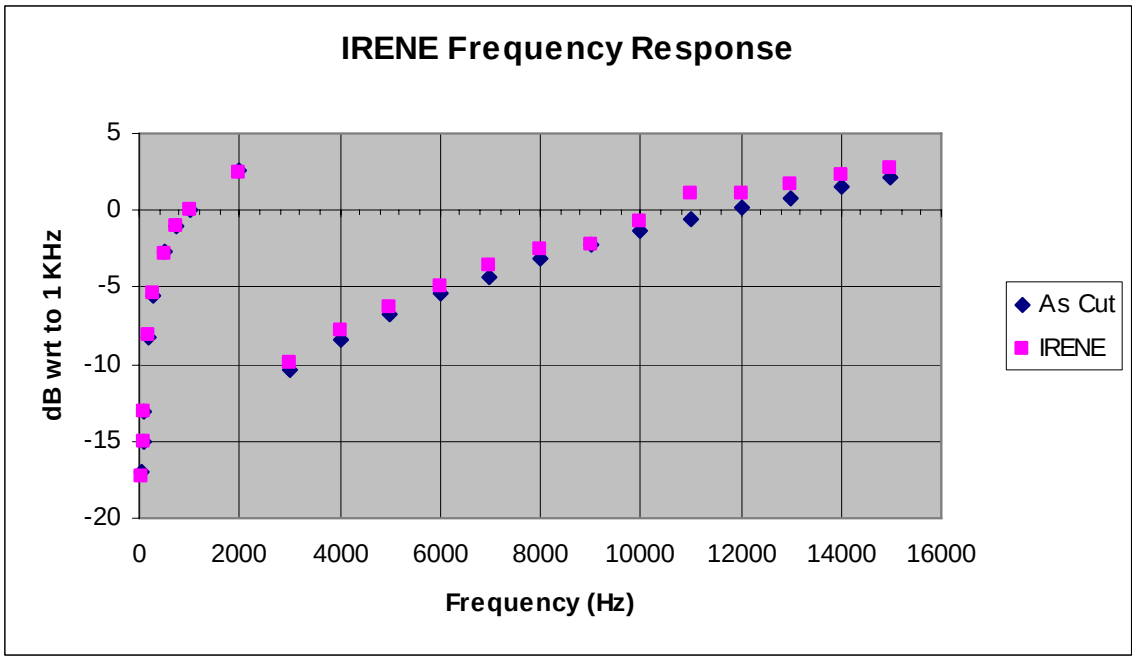


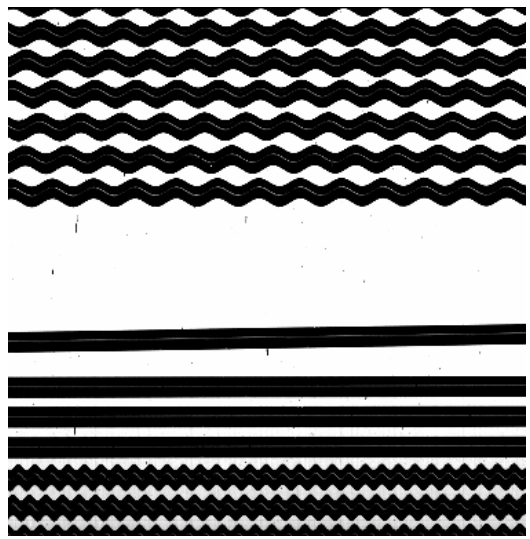
Testing and Validation Phase

- 9-12 months in duration in the LC Recording Lab
- Led by Peter Alyea
- Machine 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

Test Discs

Study of frequency and amplitude response, and noise with specially cut lacquer discs





Pristine new acetate disc scanned by IRENE

Double Check Stomp

Duke Ellington, 1930

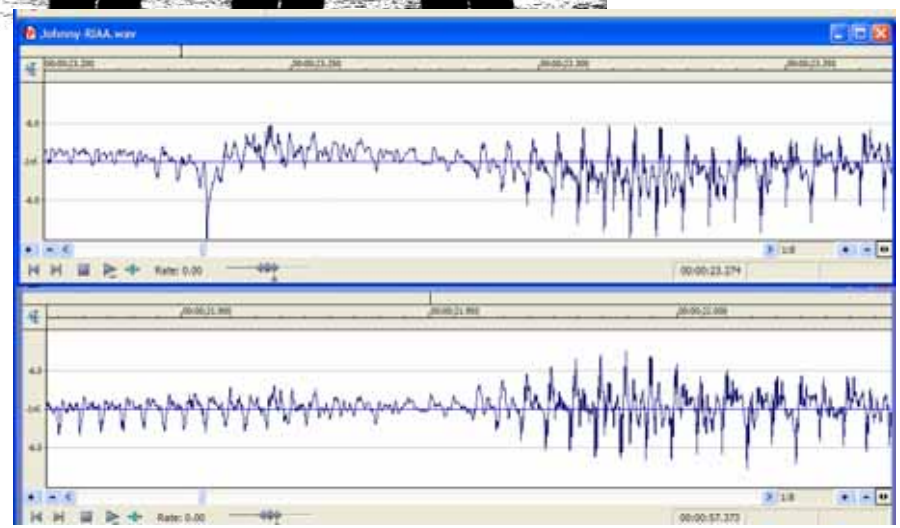
Comparison: Shellac disc in good condition, disc cleaned before stylus transfer, IRENE transfer before cleaning

Stylus, optimized, cleaned

IRENE
Not cleaned

“Johnny”: Les Paul and Mary Ford

1953 recording, shellac 78 rpm disc is worn and scratched, distorted



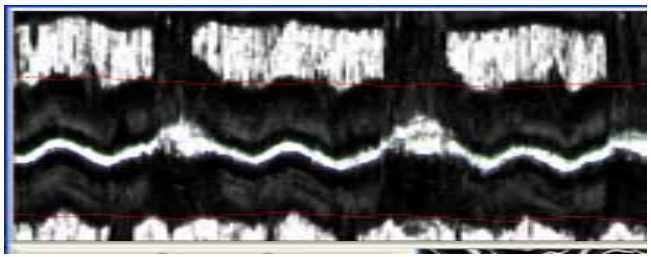
Stylus version has a clear skip due to scratch

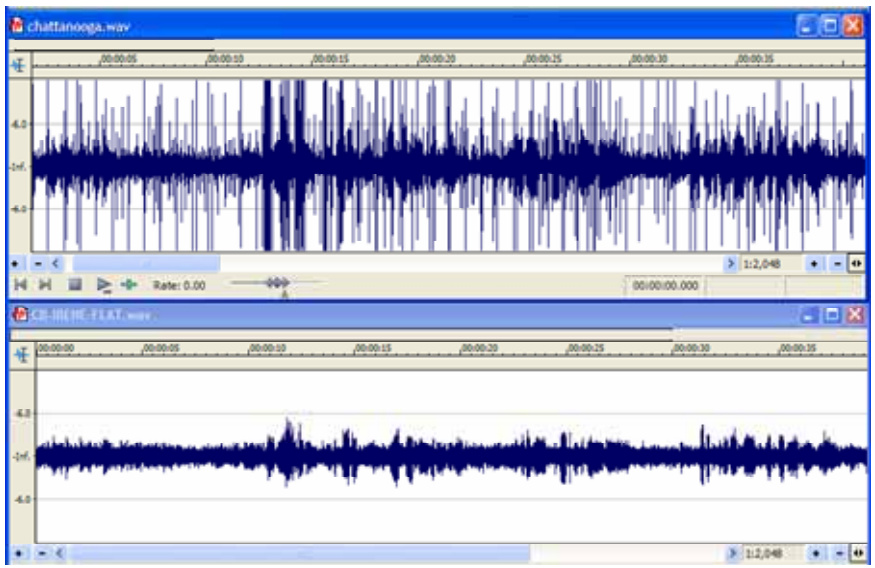
IRENE

Chattanooga Blues 1923

Ida Cox, Paramount 12063

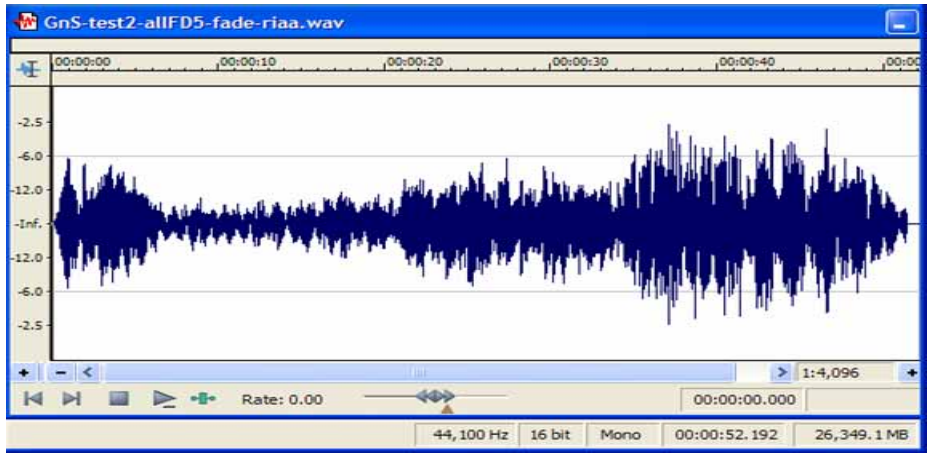
Acoustic recording, heavily worn, cracked, with significant stylus damage and distortion

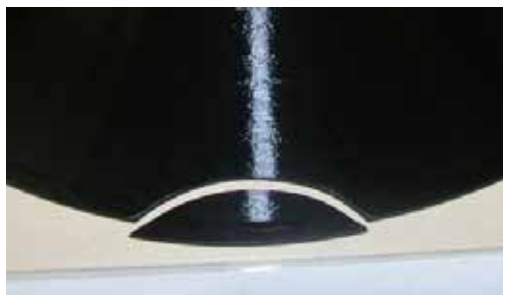


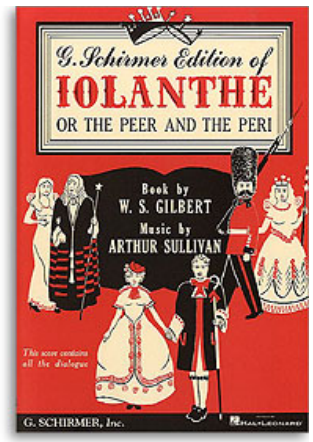


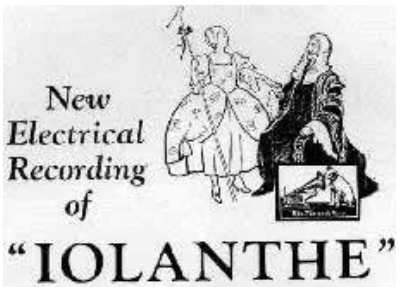
Broken Record

Gilbert and Sullivan "Iolanthe" 1930 Victor 9708





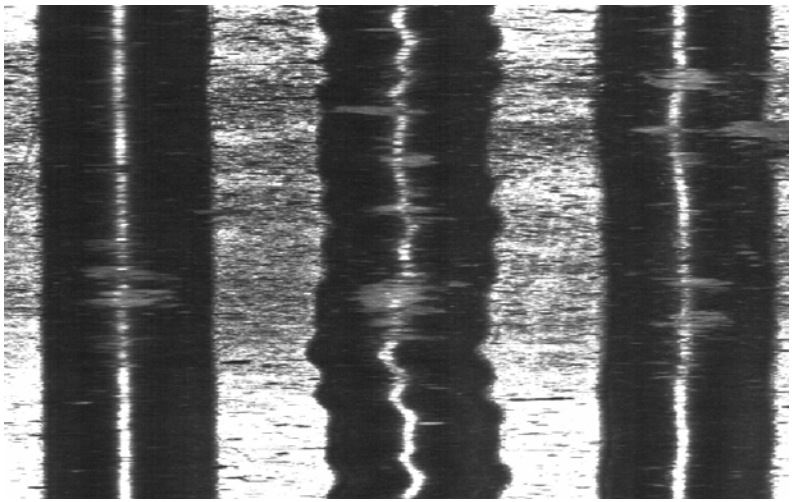




Hemlock Blues

David Lee Johnson early 1950's

Private collection: "unplayable"
Very worn, bumps on surface
Poor image quality: limit of this approach



IRENE

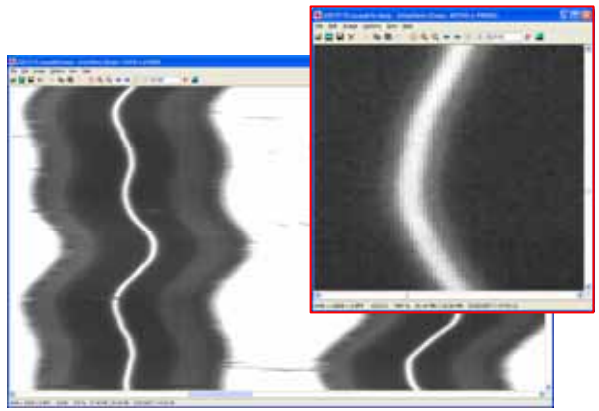
IRENE + post processing
Noise subtraction, 5KHz filter

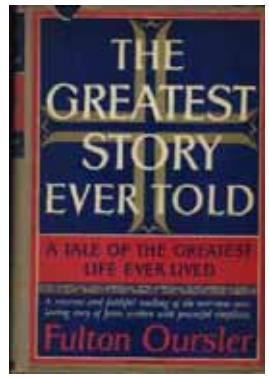
Lacquer Transcription Discs

Stylus

33 1/3 rpm, 16 inch radio transcription discs ~1950

IRENE





Theos Bernard, 1939, 10 inch disc, 78 rpm
Early western visitor to Tibet

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

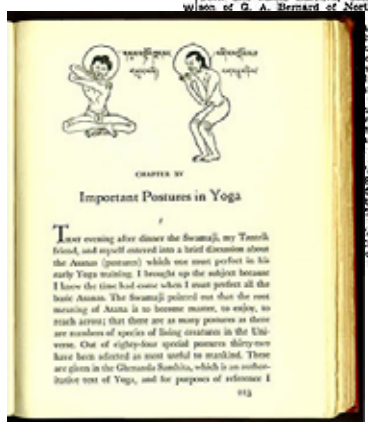
Theos Bernard, Author, Feared Dead by Wife Who Reports Incident in New Delhi

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 North-

Theos Bernard

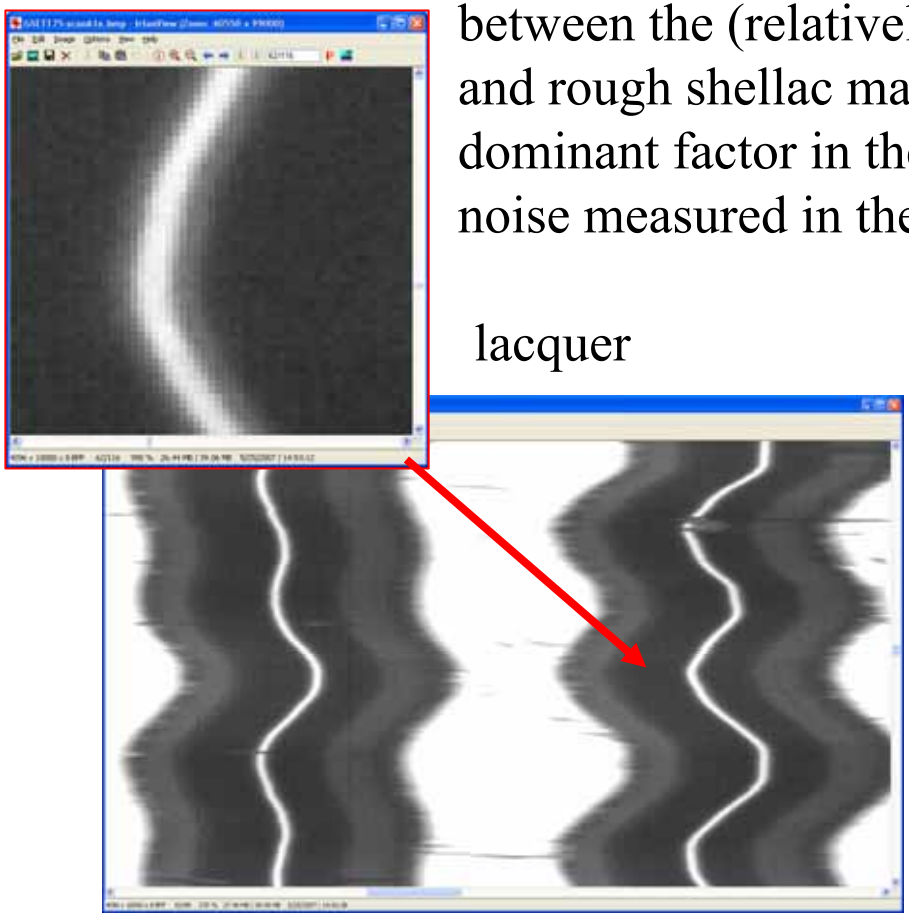
Oriental Philosophy from Colum-



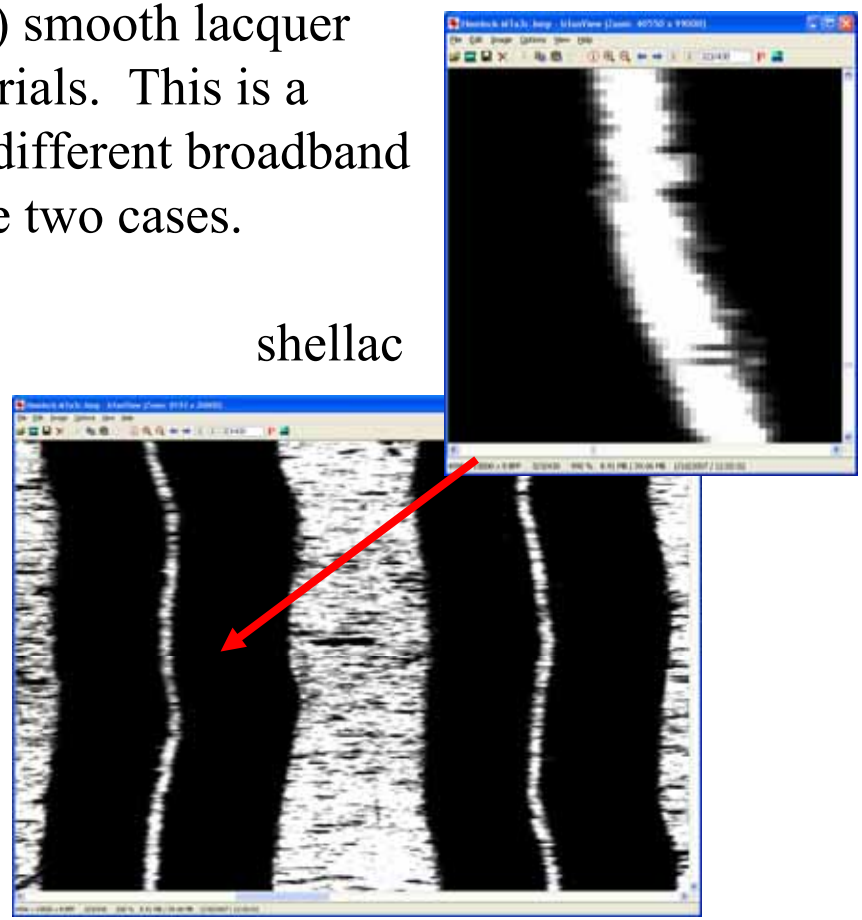
Media Characteristics

Imaged featured differ considerably between the (relatively) smooth lacquer and rough shellac materials. This is a dominant factor in the different broadband noise measured in these two cases.

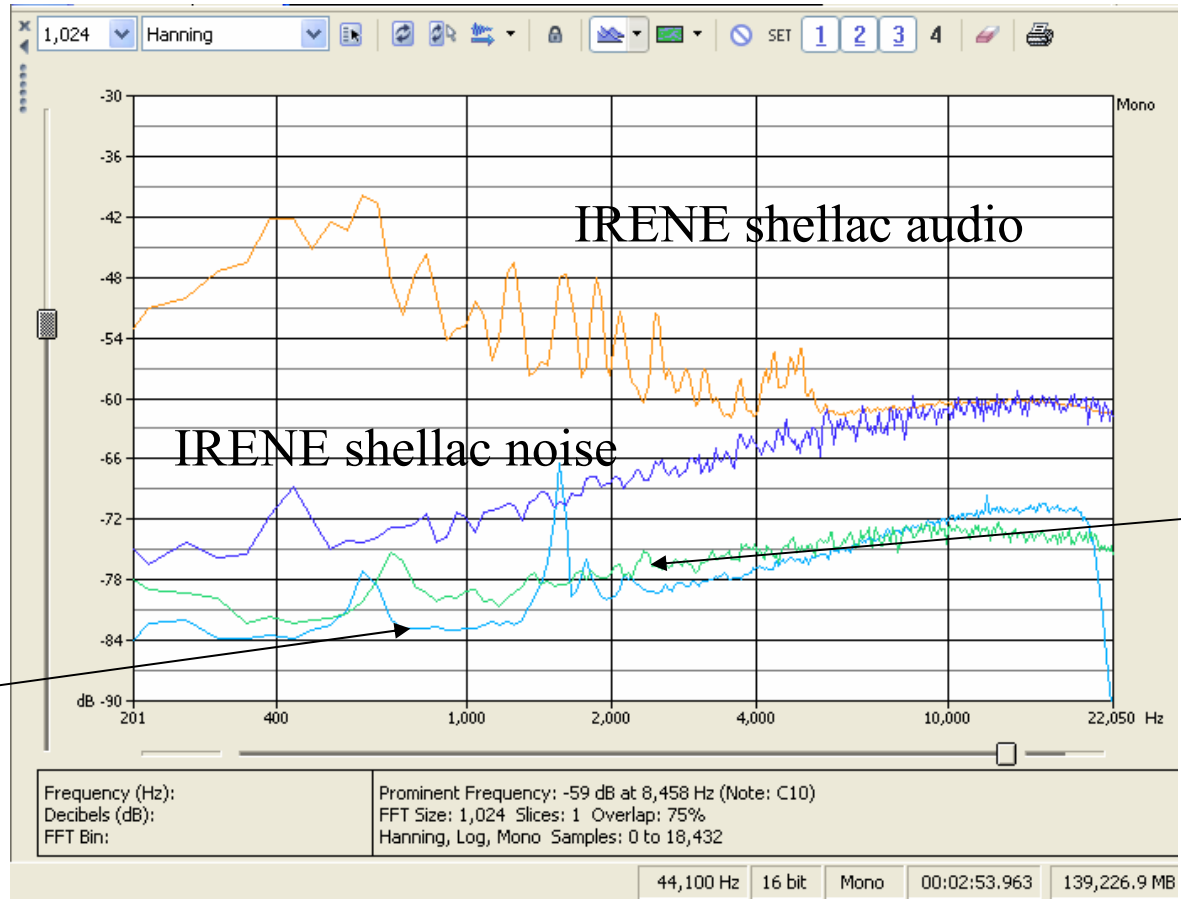
lacquer



shellac



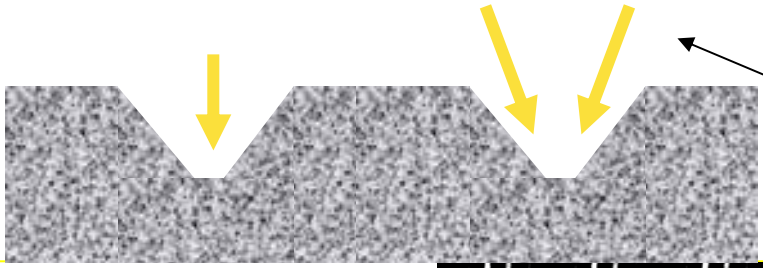
Material	Noise Level at 1 KHz, below reference
Typical audio content on shellac	Defined as a reference
Same disc, quiet track IRENE	20-25 dB
Clean shellac disc, stylus version	30 dB
Pristine lacquer, IRENE	34 dB



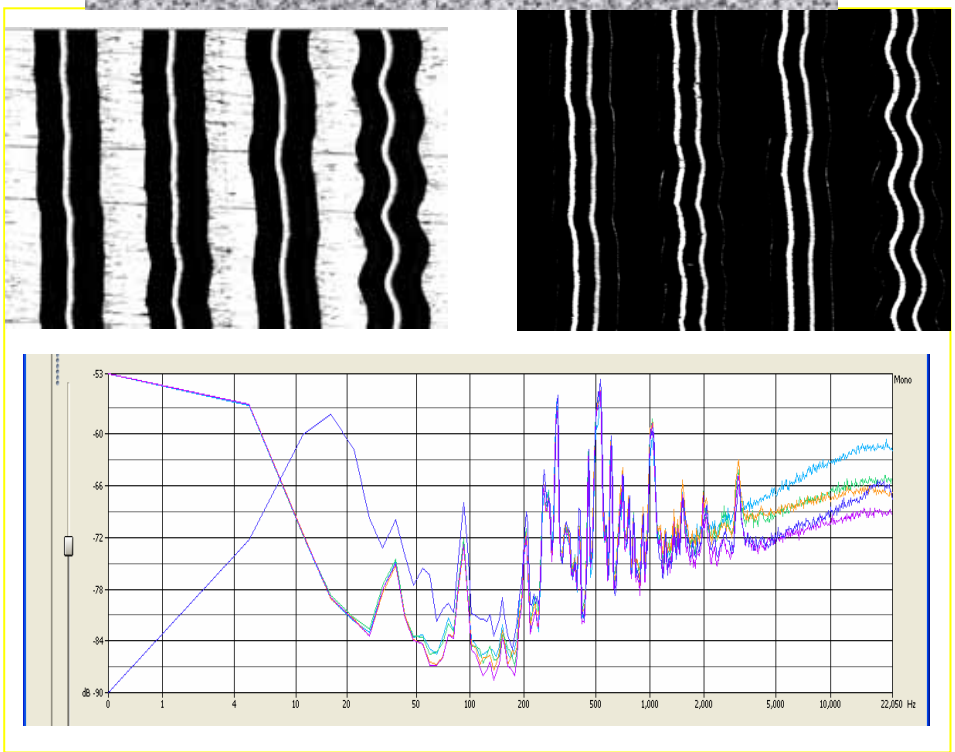
Stylus on shellac

IRENE lacquer

Alternative Illumination



Side light fixture



IRENE with vertical light (1 band)

IRENE with vertical plus side light (3 bands total)

Redundancy leads to some noise reduction at the expense of complexity

What Have We Learned?

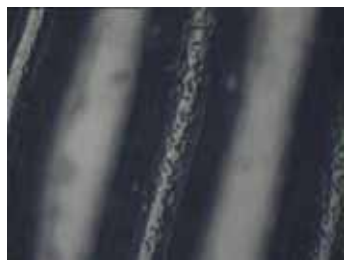
- Hardware Performance
  - Illumination
  - Focus methods
- Fidelity and Noise
  - Frequency response
  - Broadband noise levels
    - Varies between shellac and lacquer
    - Sensitive to focus
    - Insensitive to feature detection, illumination, sampling rate
    - Multiple feature detection

IRENE: Summary and Outlook

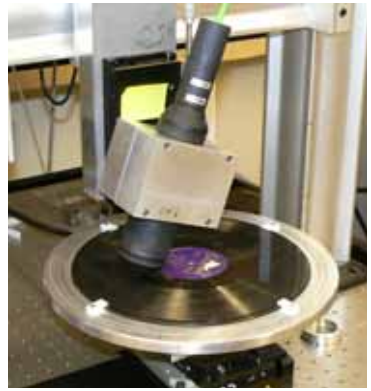
- Project goals and deliverables were satisfied
- Considerable insight into 2D optical scanning on a wide range of materials
- Particular performance on damaged media – can be developed further into an actual tool
- Broad band noise on shellac greater than lacquer, and stylus version, due to imaging response of the media
- 3D scanning will lead to greater redundancy and lower noise levels would be expected

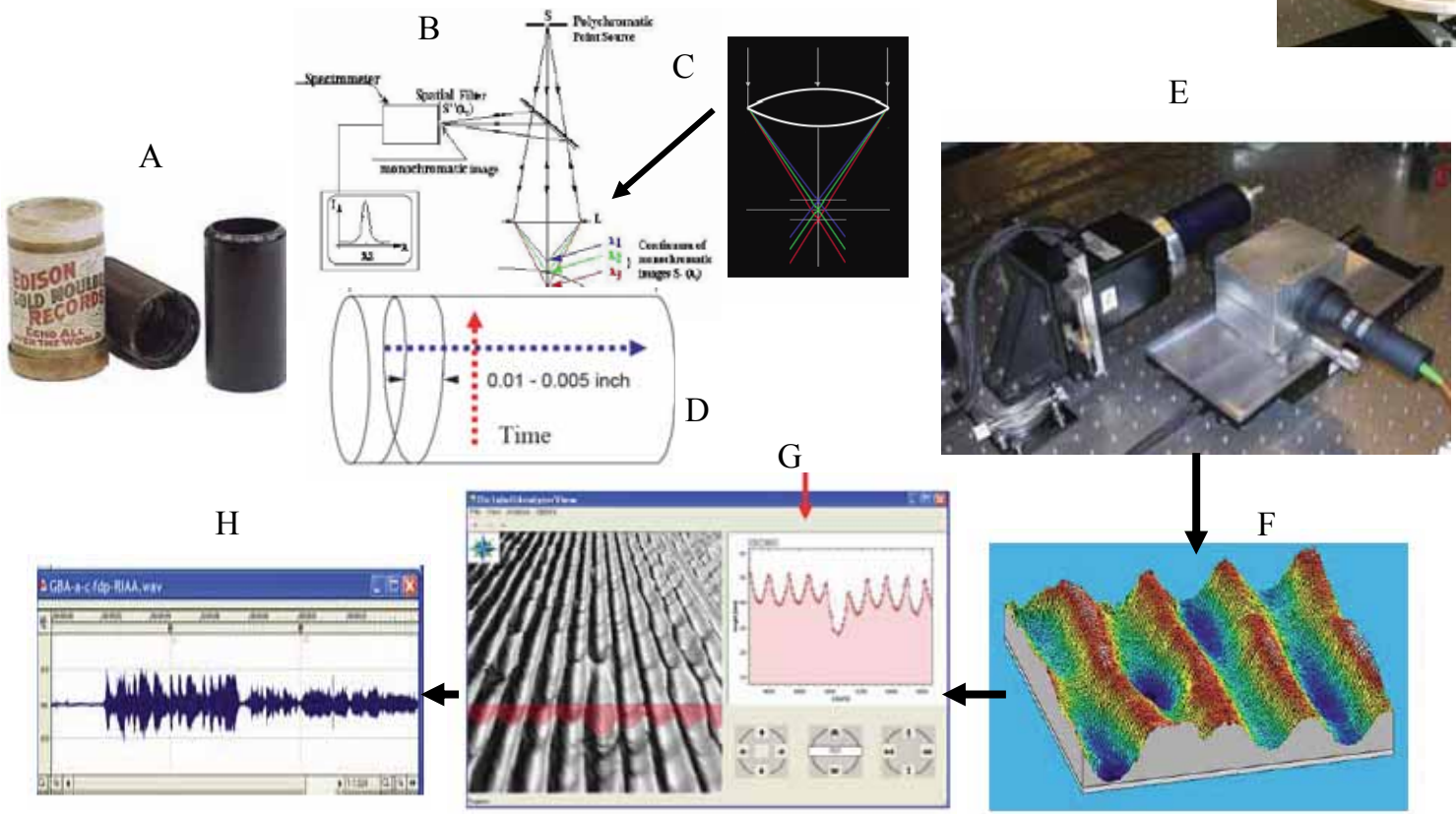
3D Imaging

- Wax cylinders
  - Damaged
  - Mold
- Edison commercial cylinders
- Diamond Discs
- Tin Foil
- Dictation belts
- Discs, some of which image poorly in 2D

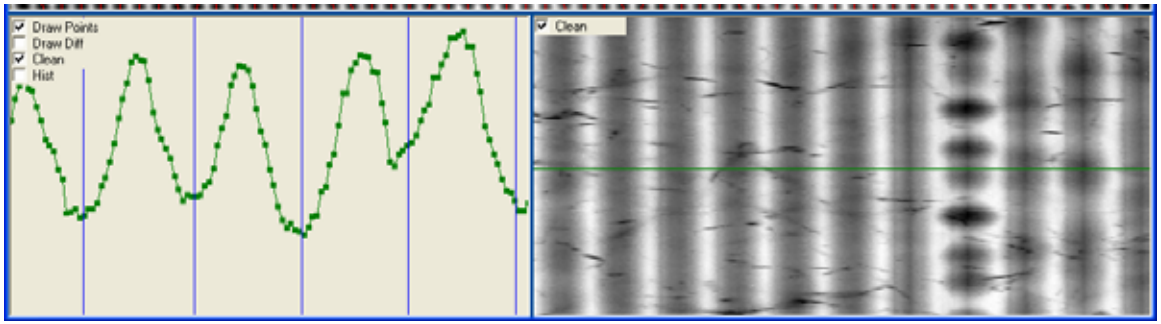


3D Scanning Process

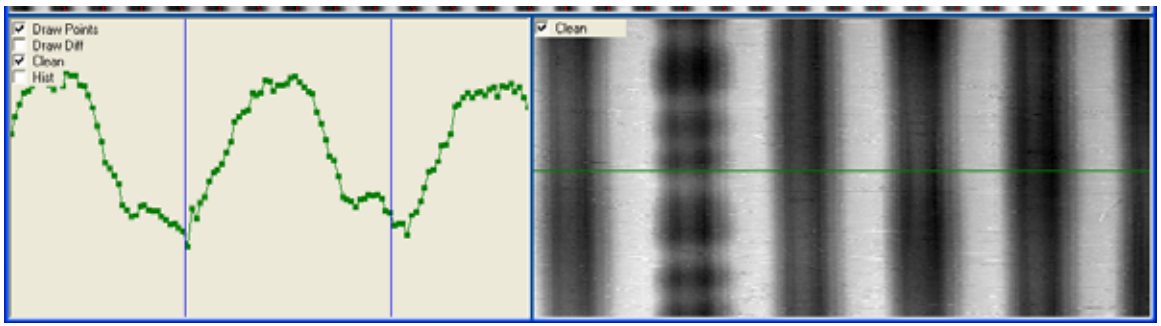




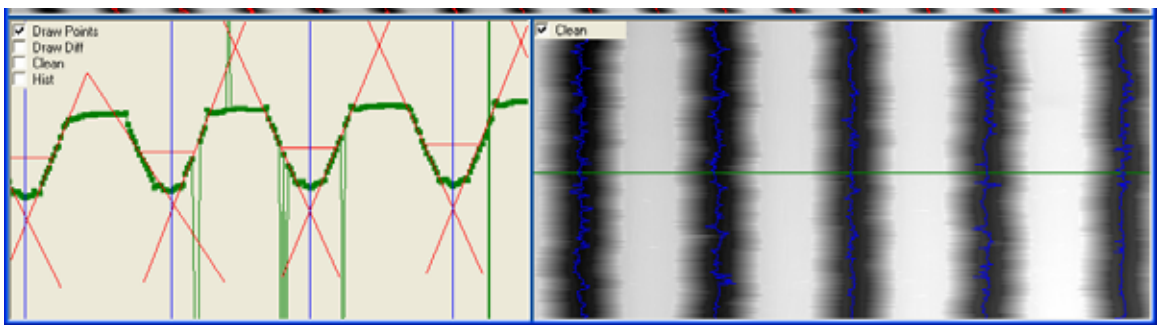
3D Images



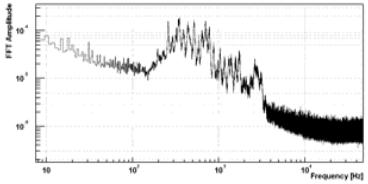
Commercial cylinder
Vertical cut



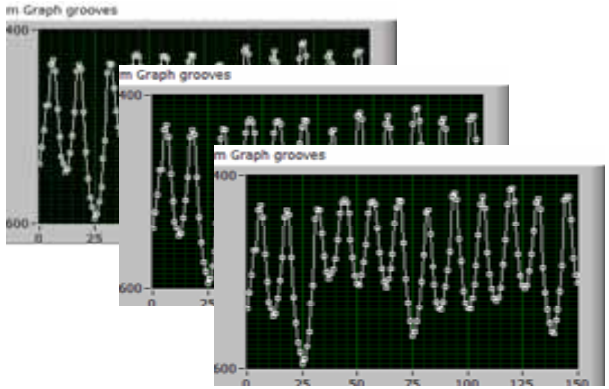
Soft wax field
recorded cylinder
Vertical cut



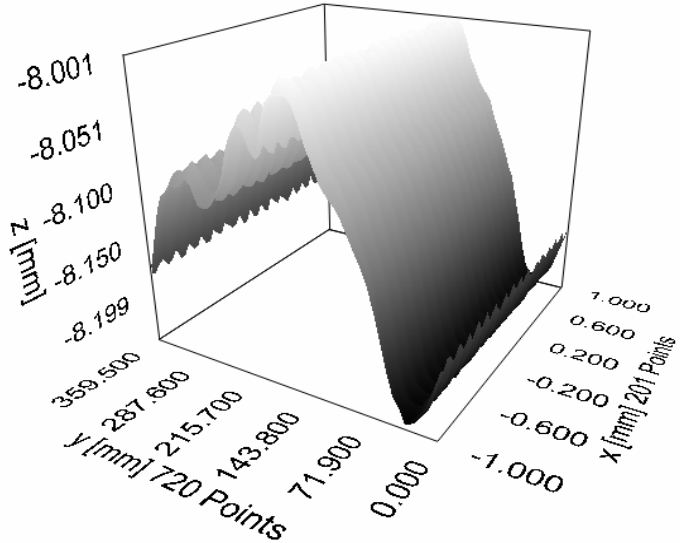
78 rpm shellac disc
Lateral cut



Sample at 96KHz to minimize effect of aliasing



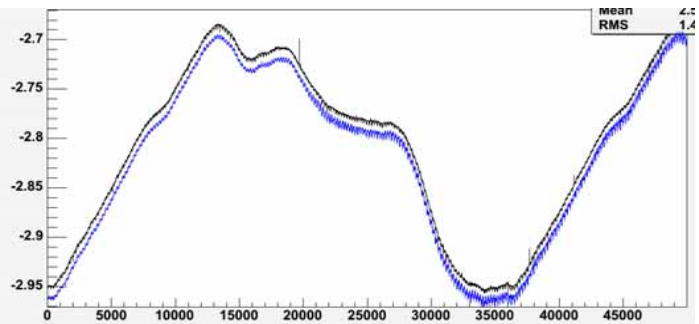
Sequential axial scans



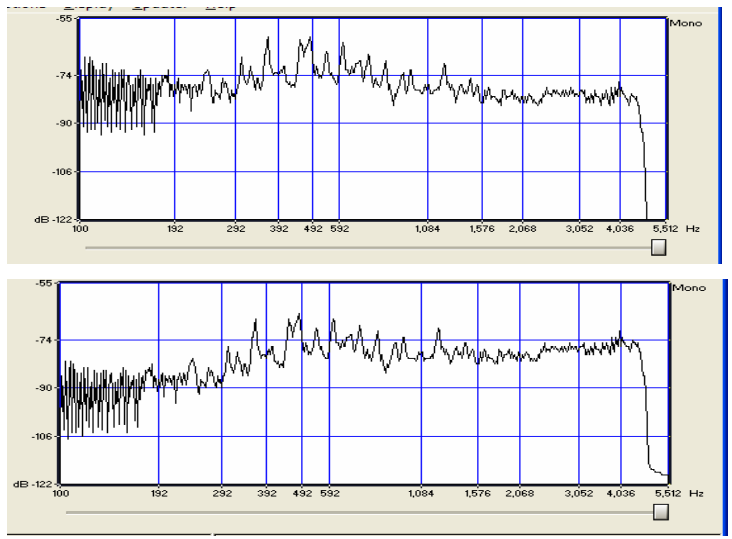
Subtract valleys from ridges to correct for overall shape

(Ridges provide (approx), geometrical reference)

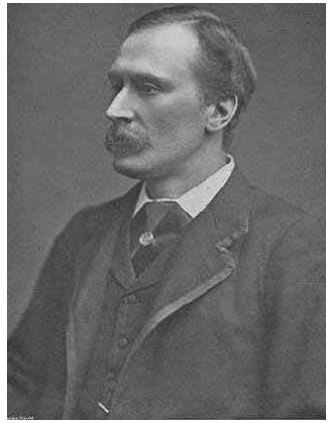
Overall cylinder shape due to off-center, deformation, heard as low freq rumble



d/dt



Sound Comparison

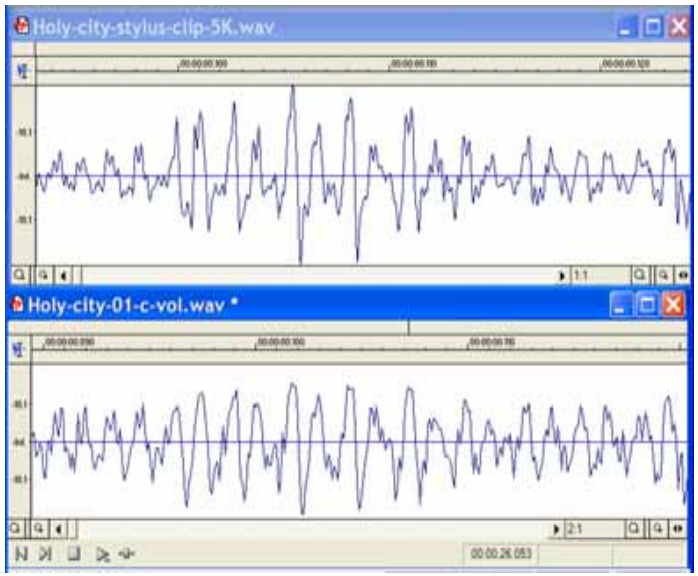


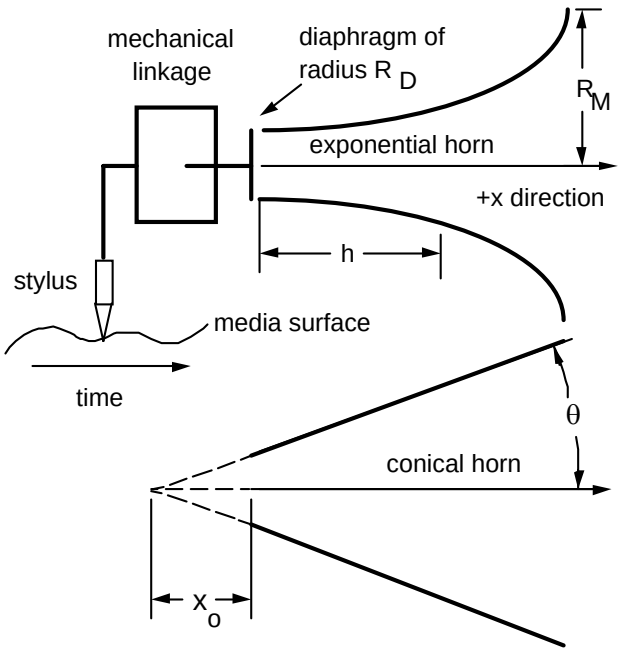
- The Holy City, composed by Stephen Adams,

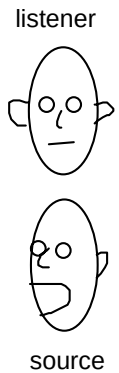
  The Edison and Skedden Mixed Quartet, Amberol 1601

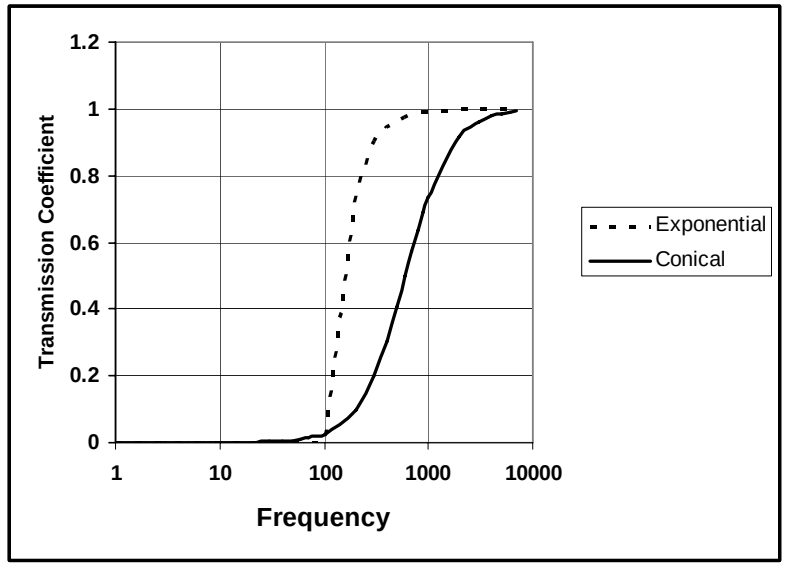
  Commercial cellulose release

- Stylus
- Optical
- Optical + filter + EQ





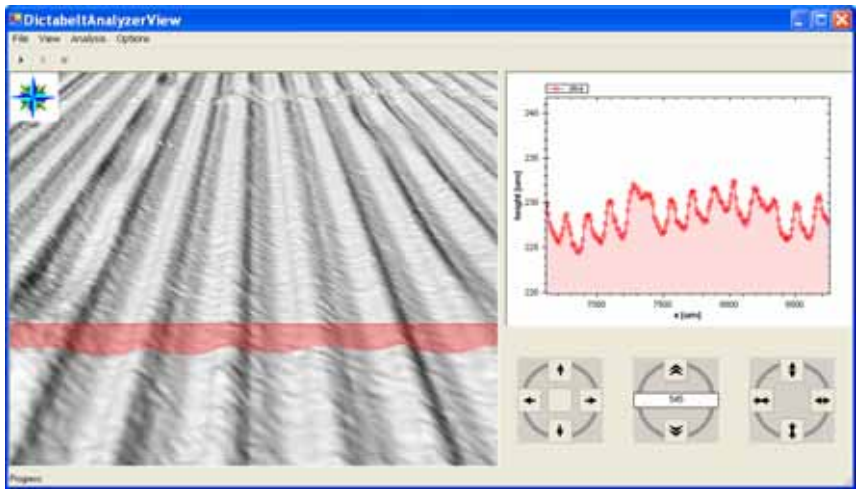


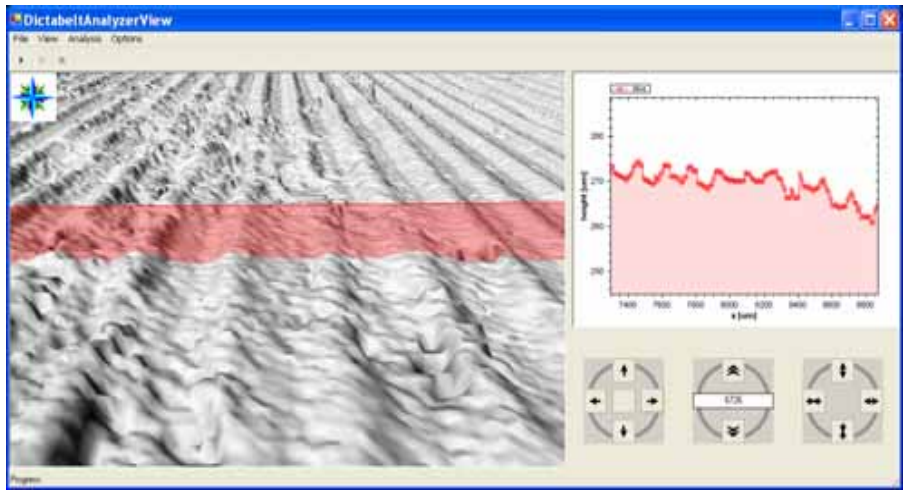


Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.

Surface Damage = Sound Degradation

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





UC Berkeley Phoebe Hearst Museum holds an extensive collection of wax cylinders recorded by Anthropologist Alfred Kroeber and others. This sample is from the set recorded of Ishi (circa 1911-14).

Sam Batwai, Alfred L. Kroeber, and Ishi

Ishi at Deer Creek

Early Native American Fieldwork Collections (partial list)

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

Pilot Study

- Wax cylinders from fieldwork collections are a good example of 3D media
  - Collaborate with UC Berkeley, Phoebe Hearst Museum and Dept. of Linguistics: California Indian recordings
- Scan a range of samples to:
  - Bracket the performance of the process
  - Assess the realistic throughput for a larger project
- Practicalities
  - Software and hardware development to enable efficient data taking and analysis.
  - Incorporate new, faster probe.

Education and Outreach

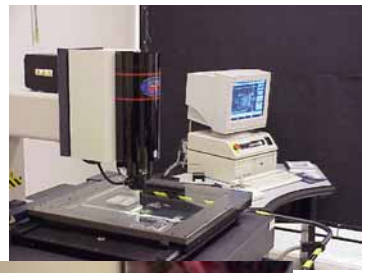
- Example of methods from the physical sciences applied to other fields of research, culture, and public service
- Interesting and novel research experience for science and engineering and students
  - 7 undergraduates from EE, Comp Sci, and Physics
- Public presentations
  - ~50 seminars, radio, TV, newspapers, magazines, blogs, >200 Google hits, hundreds of email inquiries.
- Research opportunities for students from groups under-represented in science and engineering

Prospects

- 2D disc scanning has been evaluated here with IRENE
  - High speed and robust capture of a variety of disc media
  - Address a range of damaged and delicate samples
  - Provides detail assessment of condition
  - Additional software development to make it an achive "tool"
- 3D scanning is an R&D effort at present.
  - 3D scanning of discs offers a route to lower noise transfers due to the inherent redundancy
  - Demonstrated on cylinders and dictation belts, disc study
  - Propose to develop a 3D scanner
  - Collaboration with UCB Linguistics and Hearst Museum to assess impact on Native American fieldwork recordings
  - Important implications for:
    - Early recording history
    - Fieldwork collections
    - Ultimate fidelity transfers from discs
    - Damaged media, dictation belts

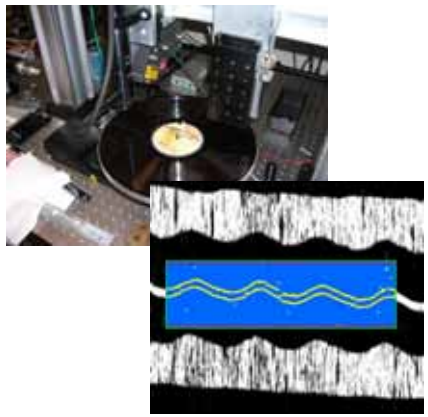
Optical Scanning: Technology Roadmap

Basic 2D concept
demonstration
40 min / 1 sec

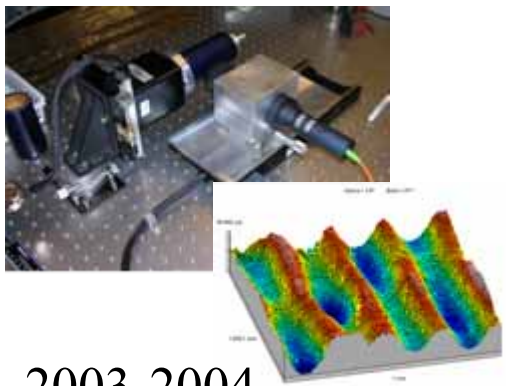


2002

2D disc R&D
4 sec / 1 sec



3D cylinder R&D
20 hr / 1 min



2003-2004

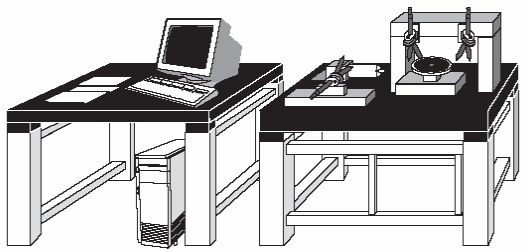
IRENE
System eval

2006-2007

Production
mode discs

2008?

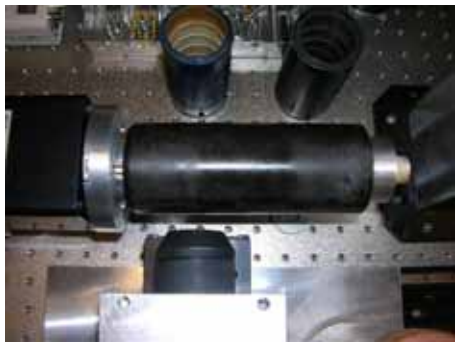
3D System
10 min / 1 min

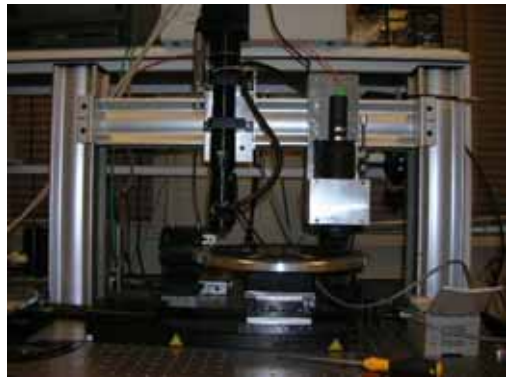


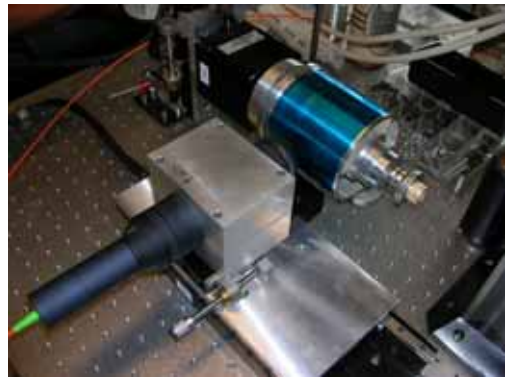
2007-2008 ?

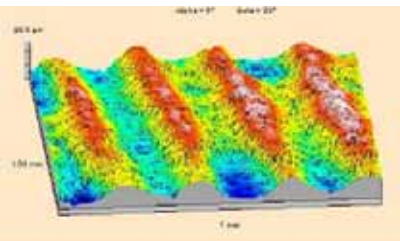
Pilot
study

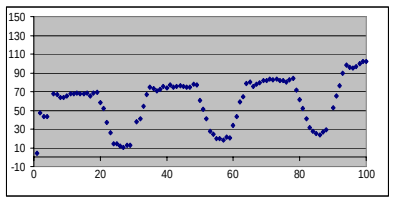
Optical Scanning: A general tool to preserve and create access to recorded sound history

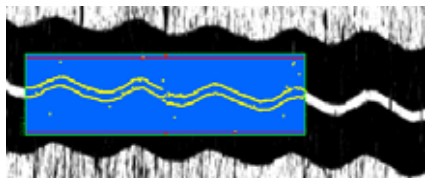












Wax cylinder

Shellac disc

Plastic dictation belt

Web site URL: http://irene.lbl.gov/

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).