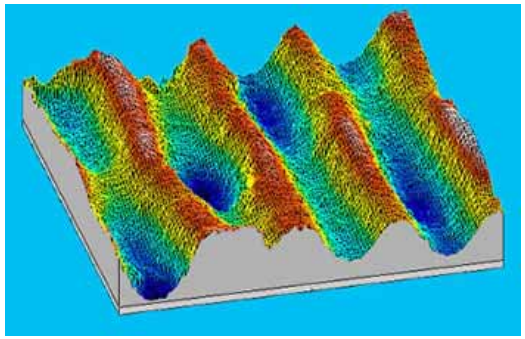
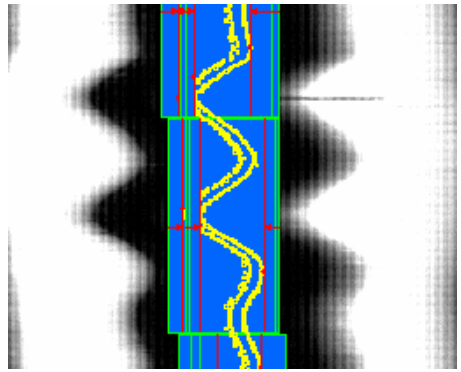




Imaging Lost Voices: Optical Scanning Applied to Recorded Sound Preservation and Access

Carl Haber

Lawrence Berkeley National Lab

Collaboration and Support

Lawrence Berkeley National Lab: Earl Cornell, CH, Vitaliy Fadeyev, Robert Nordmeyer, Jian Jin, Mitch Golden

Library of Congress: Peter Alyea, Larry Appelbaum, Dianne van der Reyden, Elmer Eusman, Eric Hansen

UC Berkeley: Andrew Garrett (Linguistics), Victoria Bradshaw (Phoebe Hearst Museum of Anthropology)

Fantasy Studios: George Horn

EIF Fribourg – Switzerland: Ottar Johnsen, S.Hezel, S.Nowak

University of Southampton – UK

First Sounds

The LIBRARY of CONGRESS

NATIONAL ARCHIVES AND RECORDS ADMINISTRATION 1985

INSTITUTE of Museum and Library SERVICES

NATIONAL ENDOWMENT FOR THE HUMANITIES

THE ANDREW W. MELLON FOUNDATION

John Simon Guggenheim Memorial Foundation
Fellowships to Assist Research and Artistic Creation

Preservation Science

- Materials analysis and processing
  - Stabilize, preserve, repair media: inks, paper, pigment…
  - Archaeometry, linkage between materials and history
- Dating
- Metrology
- Imaging
- Restoration
- Physics and chemistry of information storage and retrieval
  - "Signal" analysis
  - Degradation mechanisms
  - Legacy media and playback

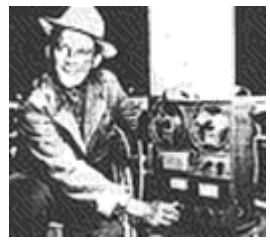
History

- 1853 Leon Scott: *Phonoautograph* paper recorder
- 1877 Thomas Edison invents sound reproduction on tin foil *Phonograph*
- 1885 Bell and Tainter introduce wax cylinder
- 1887 Emile Berliner invents disc *Gramophone*
- 1925 Western Electric *Orthophonic* (electrical) system

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

  end of the "**Analog Era**"
- 2001 Apple *IPOD*
- 2008 Massive online access to digital sound files

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



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

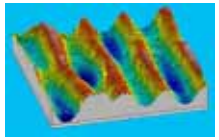
Heritage Health Index 2005

- US museums, libraries, and institutions collectively hold 4.8 Billion items
- 46.4 million sound recordings
  - 9.6 million are in grooved formats
  - 59% of these are in unknown condition
  - And there is the rest of the world
- Archivists want to reformat all pre-digital media since playback systems are not maintained
- **National Recording Preservation Act of 2000** "A bill to…maintain and preserve sound recordings and collections of sound recordings that are culturally, historically, or aesthetically significant…, " (Public Law 106-474; H.R.4846).

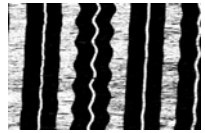
Gifted to the nation by David Woodley Packard
Opened in 2007
http://www.loc.gov/avconservation/packard/

The Berkeley Optical Sound Restoration Project

- We are developing methods of optically restoring 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, automation
  - Assessment
  - Obsolete formats and legacy playback systems
- The approach evolved naturally out of methods of optical metrology, pattern recognition, image processing, and data analysis we use for physics research.

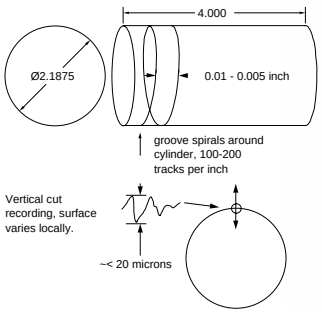


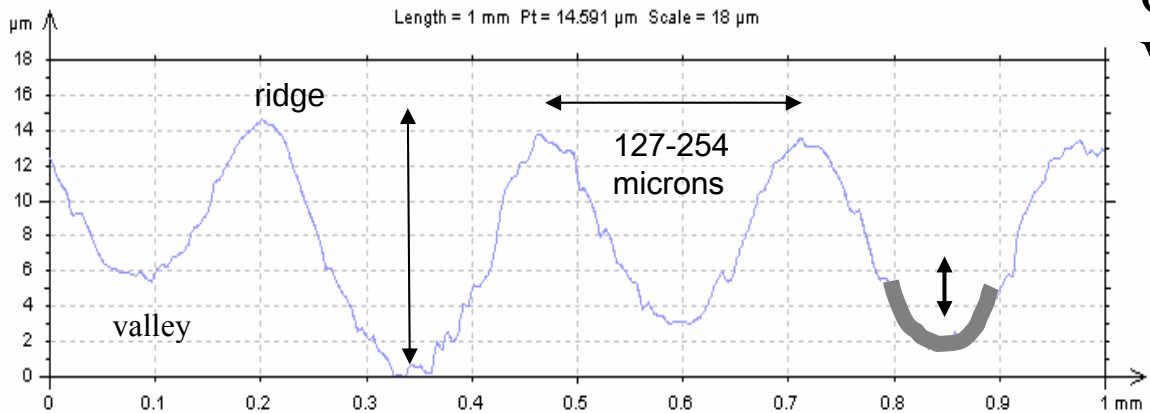
Non-Contact Digital Imaging



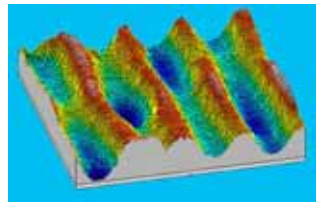
- Create a high resolution digital map of entire surface
- Computer plays record (image) with a virtual stylus
- Product
  - Standard digital sound files (ie .wav)
  - High resolution digital images which may be reanalyzed later as well
- Protects samples from further damage
- Repair existing damage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

A “smart” copying machine for records

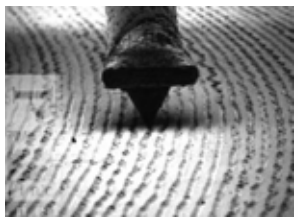


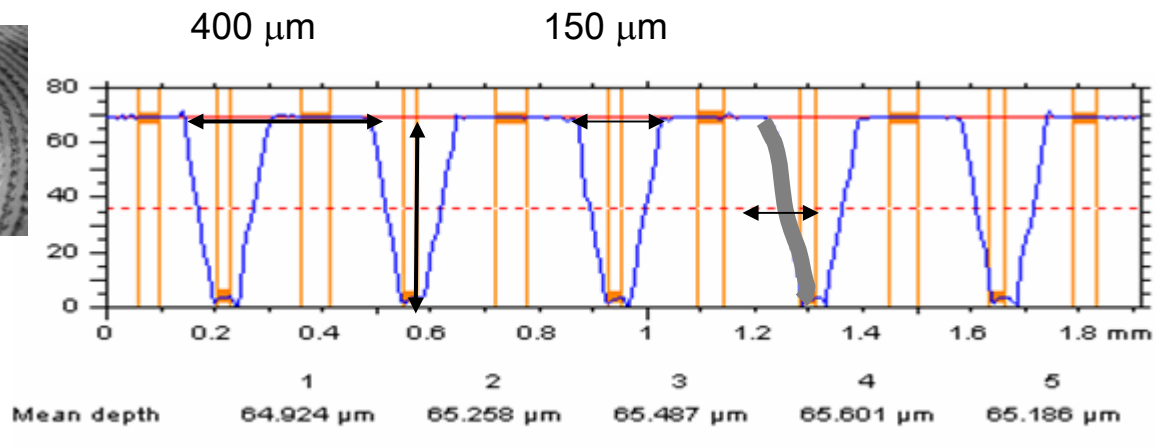


Cylinder surface
Vertical cut

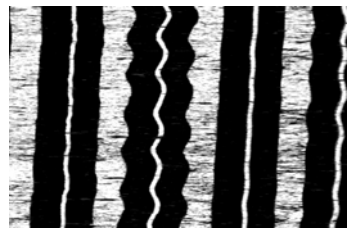


3D image





Disc surface
Lateral cut

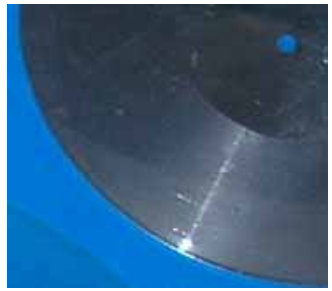


2D image

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

Sound Carrier Diversity and Condition

Wax cylinders
Fungus
Wax bloom



Al disc: oxidation

Acetate: flaking

exudation

Plastic belts
breakage

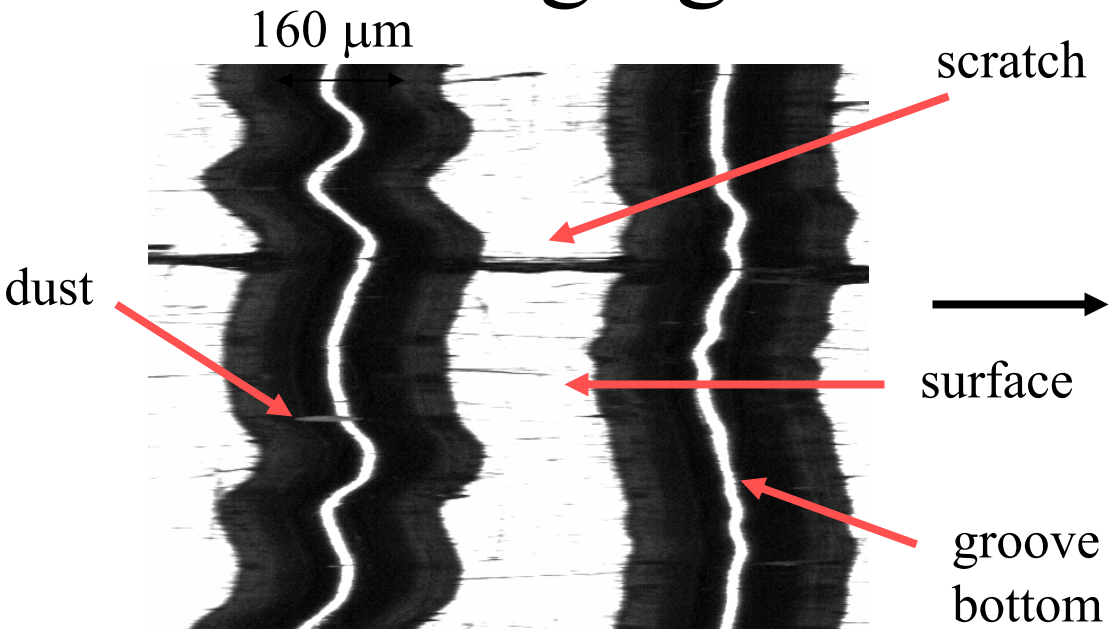
dirt

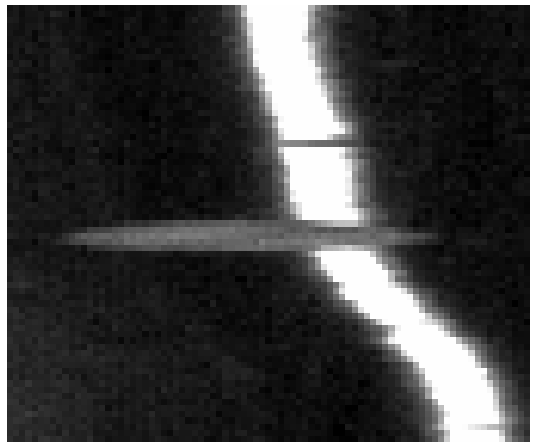
warpage

The Method

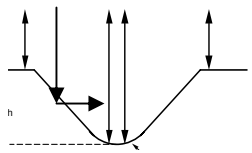
- Digitally image the surface
- Cover with sequential views or grid.
- Stitched together: surface map
- Process image to remove defects
- Analyze shape to model stylus motion.
- Sample at standard frequency
- Convert to digital sound format.
- Real time playback is not required
- Store results as standard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

2D Imaging: Electronic Camera

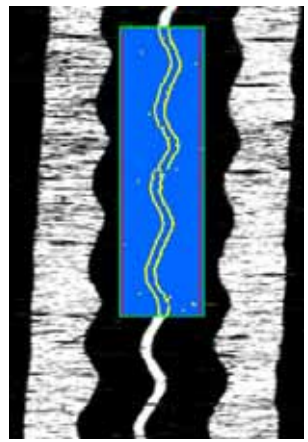




Coaxial illumination

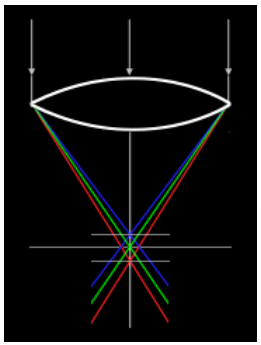


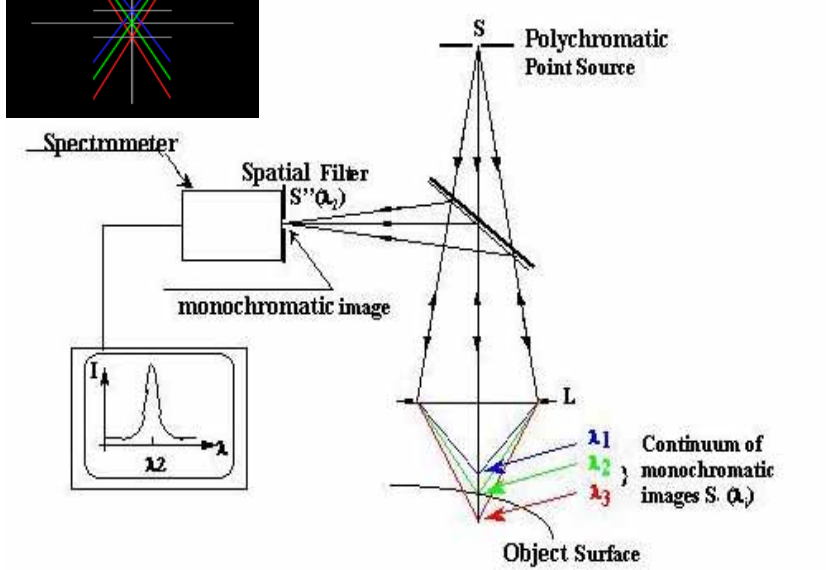
- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface
- High resolution yeilds narrow depth of field, 10 – 20 microns
- High speed cameras allow near “real-time” imaging
- Extract groove information from high contrast edge transitions

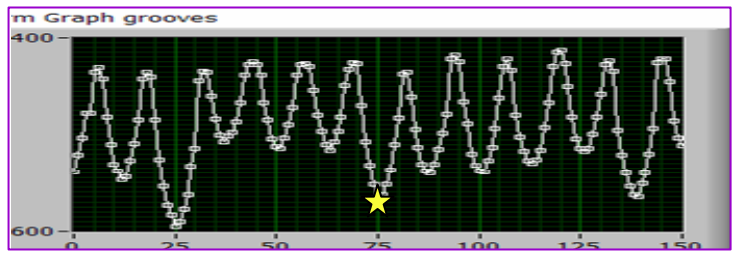


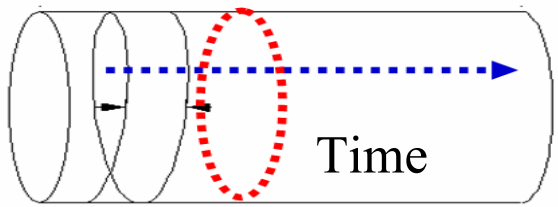
3D Imaging: Confocal Scanning Probe

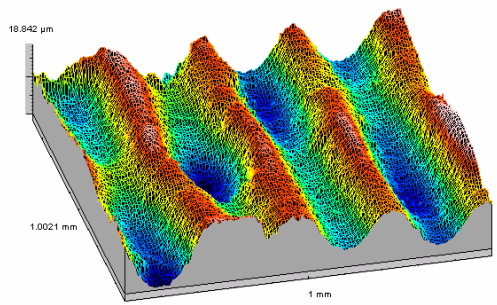
Required for cylinder with vertical groove modulation.







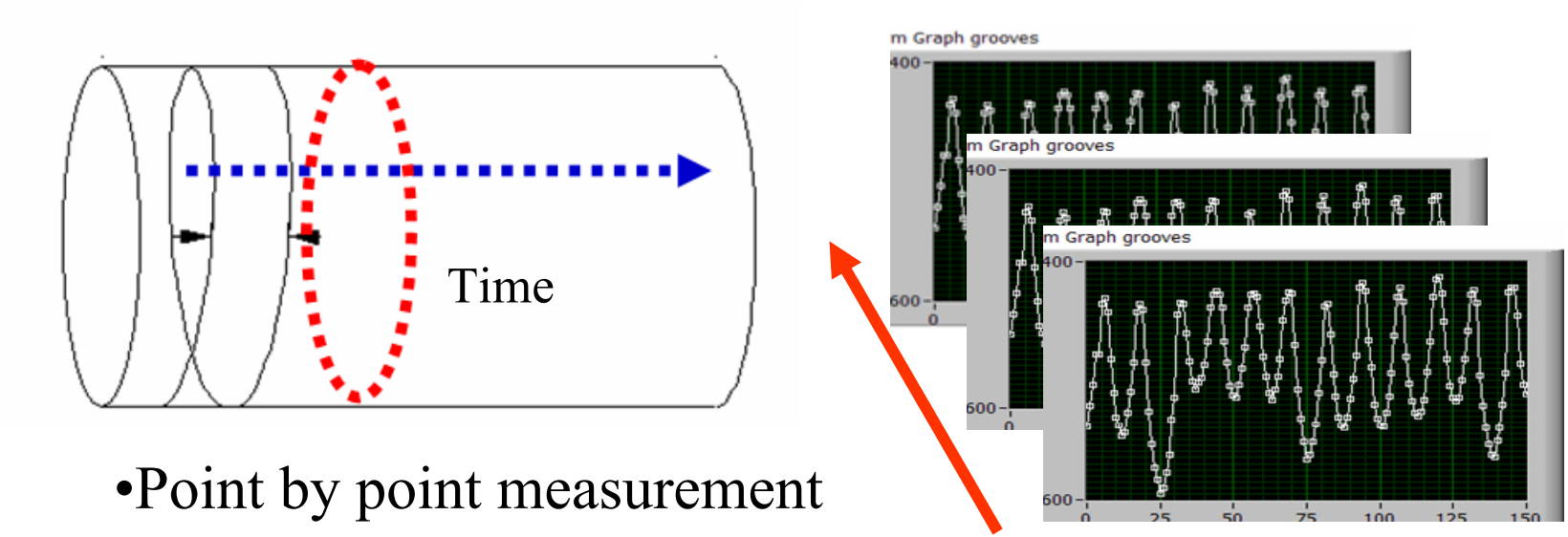




1 point at 2 KHz vs. 180 points at 1.8 KHz

3 days 30 minutes

Speed and Data

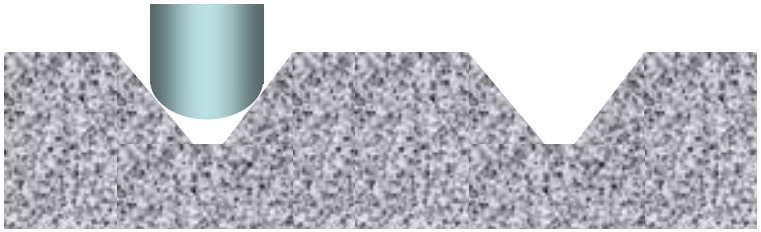


- Point by point measurement
- Exposure time per point
- Grid along time direction (red) = digital sampling
  - 0.02 degree = 18,000 samples = 48 KHz
- Grid along axis direction (blue) = points per profile
  - Typically 5 – 10 microns
- 1 probe: ~ 80 hours for 2-4 minutes of audio (2003)
- 180 probes: ~ 20 minutes (new multi-fiber probes 2008)

Redundancy

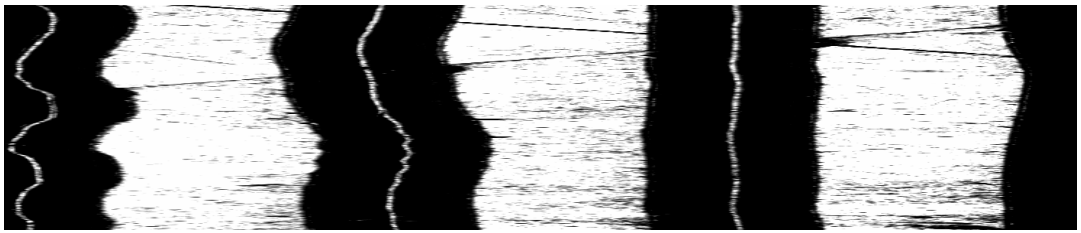
Audio stored in entire profile, signal averaging

Stylus



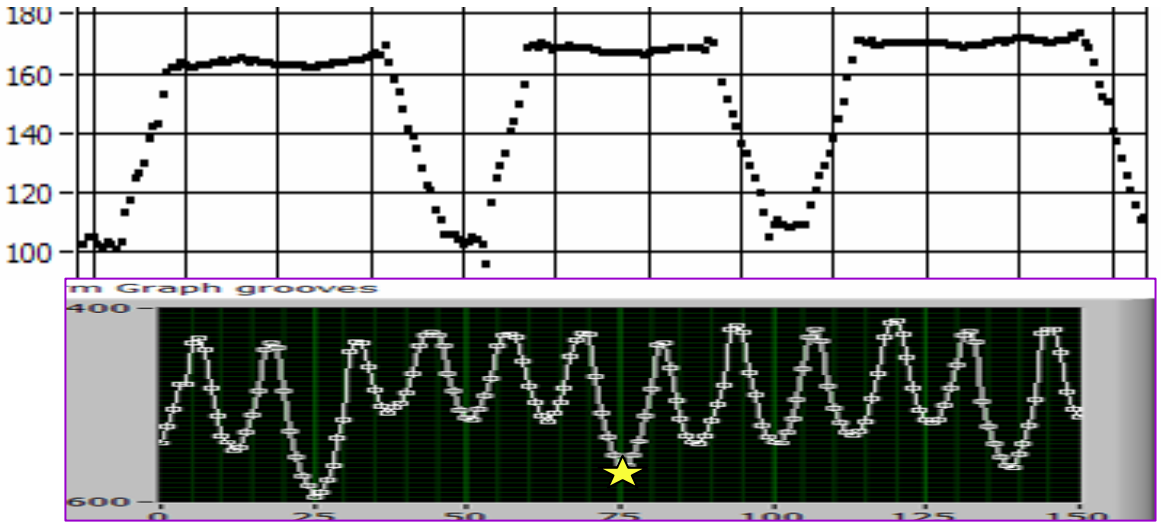
Stylus comes into contact at 2 points

2D



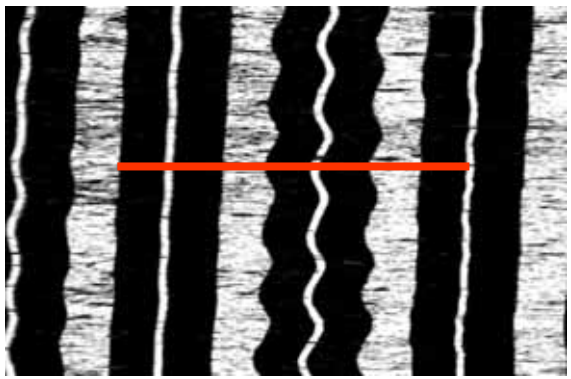
Measure the groove bottom with 2 points/slice

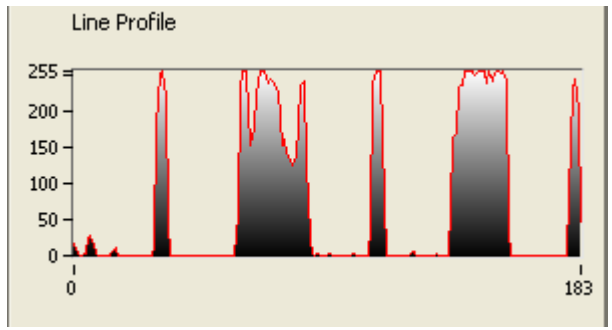
3D

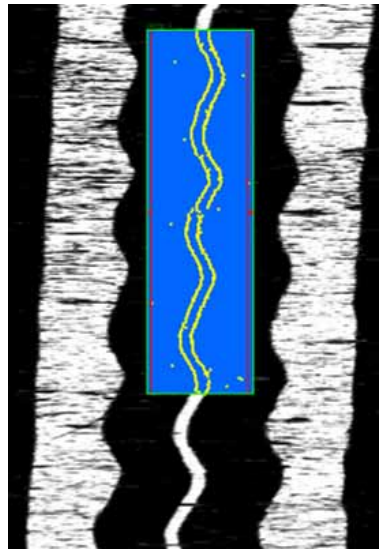


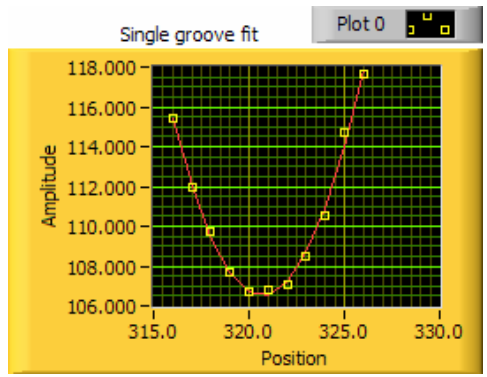
Measure the entire groove with ~30 points/slice

Image Analysis





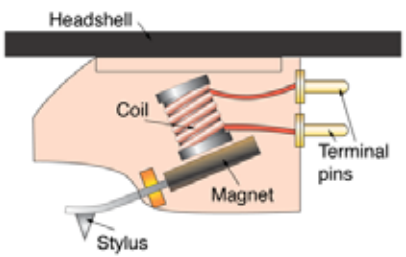




- Feature extraction and measurement
  - Importance of characteristics and algorithms
  - Control of data quality: DOF, focus, intensity
- Measured characteristics of features provide a natural noise detection and removal tool "Photoshop"
- 3D images are analyzed in an analogous fashion
  - Goodness of fit methods

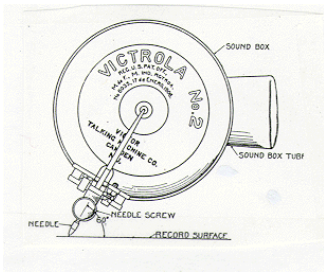
What is the relationship between "groove" and sound?

Electro-magnetic case

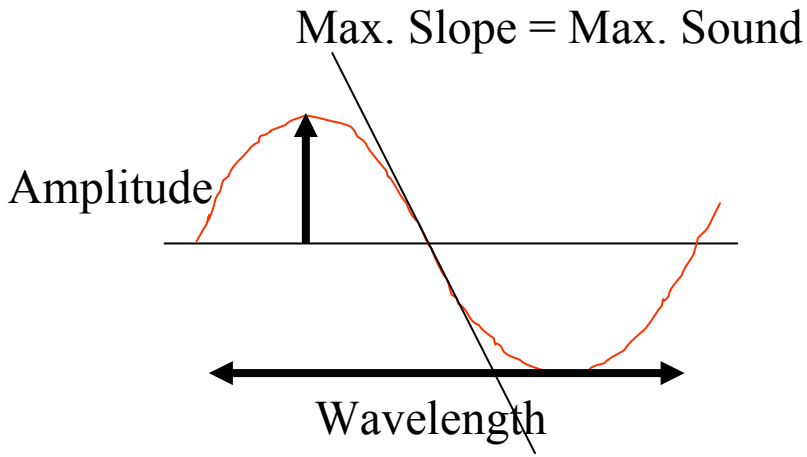


induction

Acoustic case



Diaphragm is over-damped to provide flat response



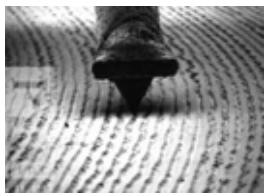
Sound = Stylus Velocity

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

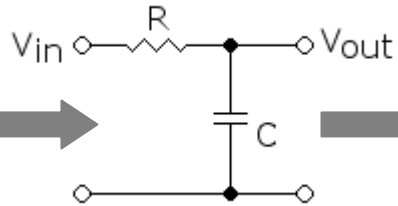
("constant velocity condition")

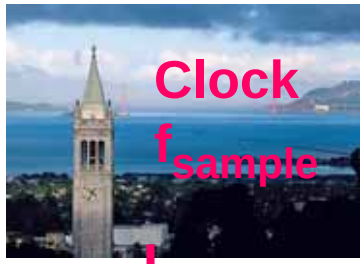
Digitization

Analog waveform

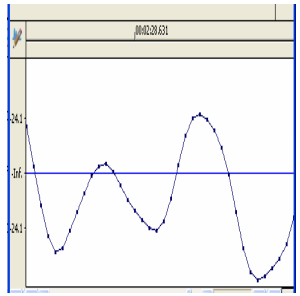


Low-pass filter
$f_0 < f_{sample}/2$

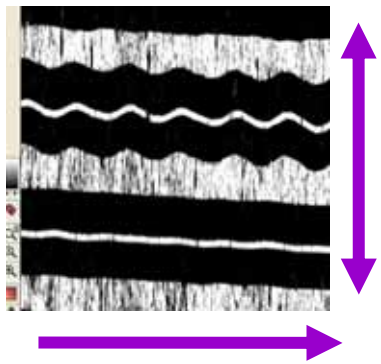




ADC



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.

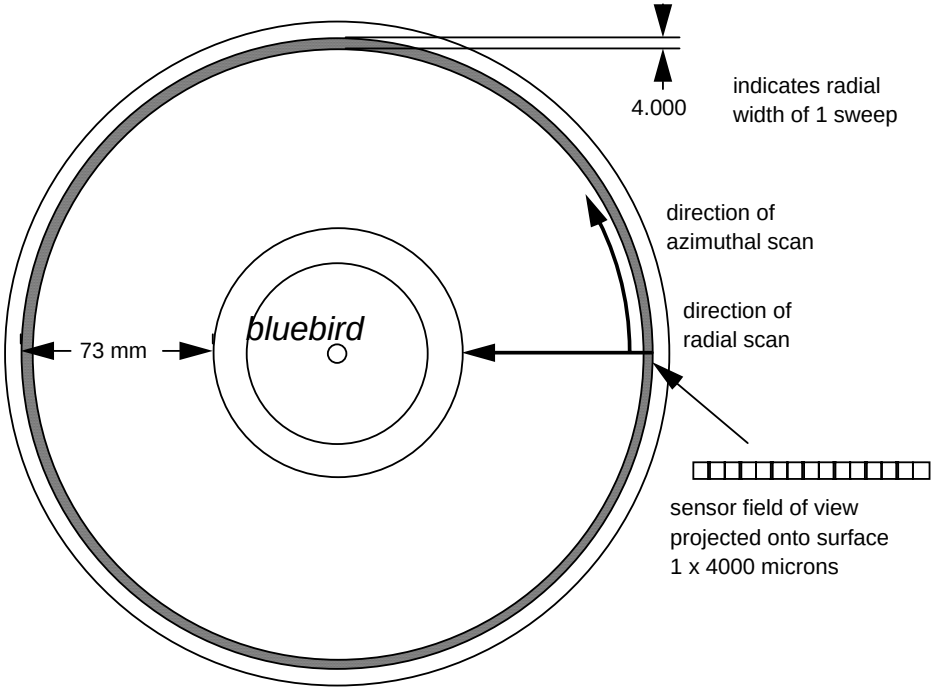
Projects Underway

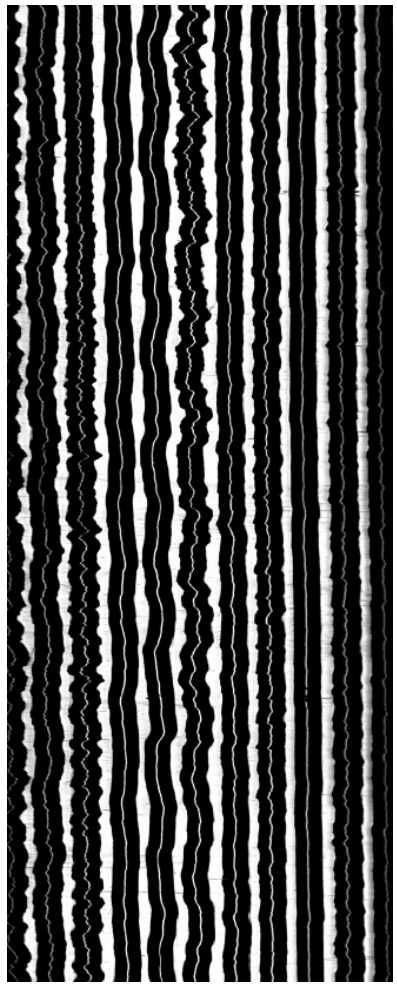
- Concept was tested 2002-2003 leading to interest and support from the Library of Congress and others.
- IRENE: a fast 2D optical scanner for disc records (NEH)
  - Digital access to the most common media + special formats
  - Installed 2006 at Library of Congress, evaluation, upgrade
- 3D: develop a fast 3D scanner for cylinders and discs (IMLS)
  - Preservation and restoration of early and damaged recordings
  - Funded 2007 by the Institute of Museum and Library Services
- Special Studies: damaged, broken, unplayable, rare
  - Wax field recorded and dictation cylinders (UC Berkeley)
  - Lacquer discs
  - Dictation belts (NARA)
  - Phonautograms
  - Foil recordings

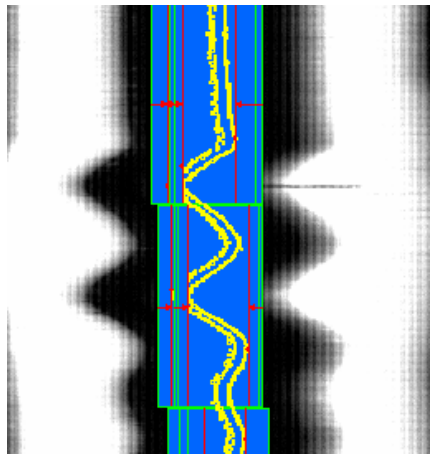
2D Scanner: Features and Goals

- 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.
- 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.
- Include a detailed evaluation phase at the Library of Congress

Line Scanning: disc is in motion



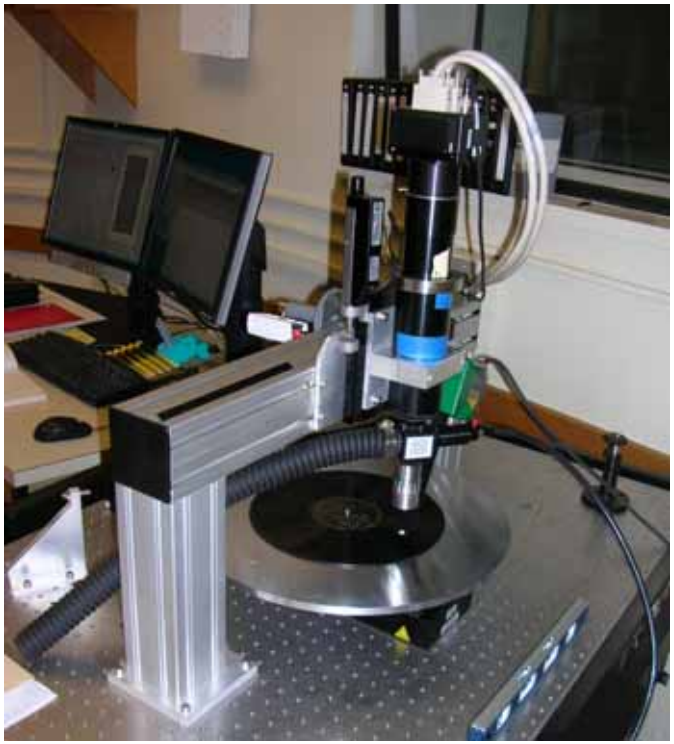


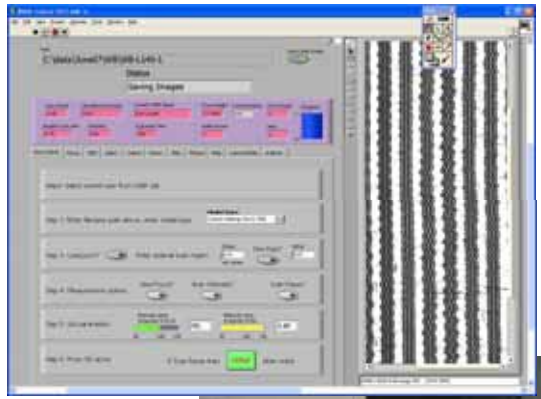


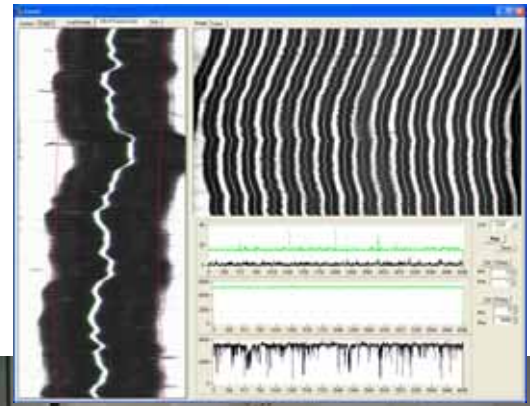
- 4000 pixels@~5x10^3 lines/s
- Requires bright illumination
- 7.6 x 10^5 lines/outer ring
  - **390 KHz max sampling**
- Scans @ a few x real time
- Scan time decreases linearly with sampling!!!.

I.R.E.N.E.

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



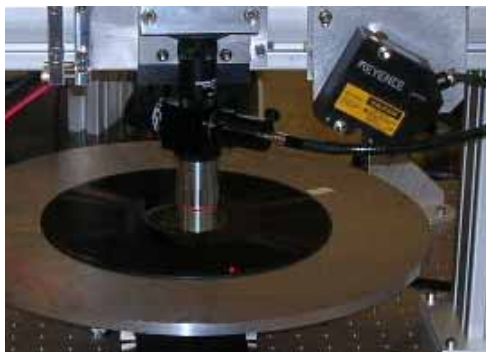




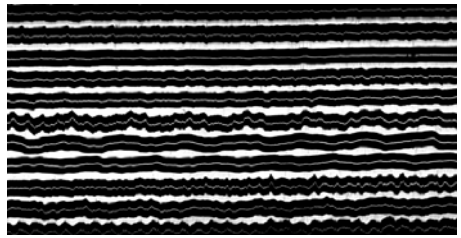
Key Technical Issues

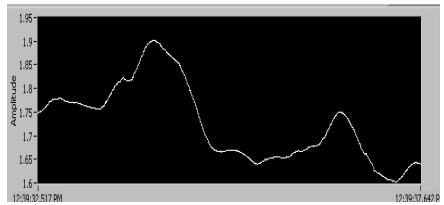
- Fast camera
- Illumination
  - Intensity, Stability, Heat
- Wide field of view optics
- Active focusing system
- Vibration Control
- Motion Control
- Image capture and processing
- Performance
  - Robustness, Frequency Response, Noise, Speed

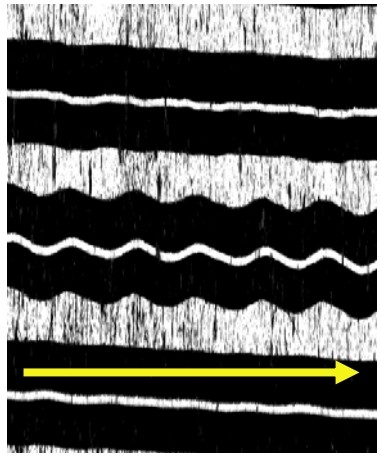
I.R.E.N.E



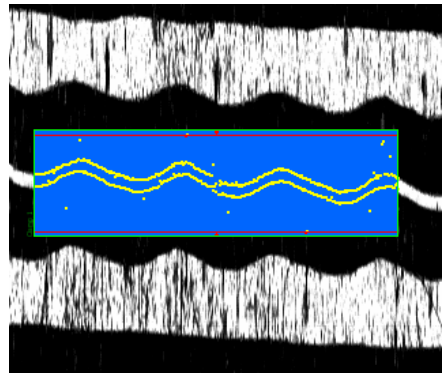
Line scan



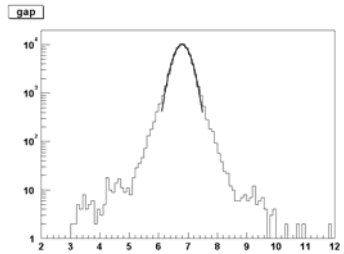




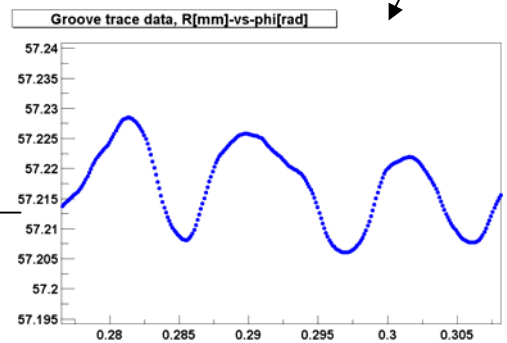
Time
Pixels = 104 KHz

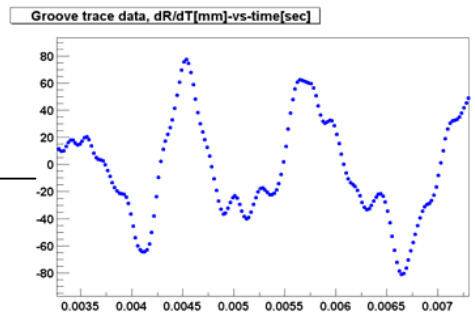


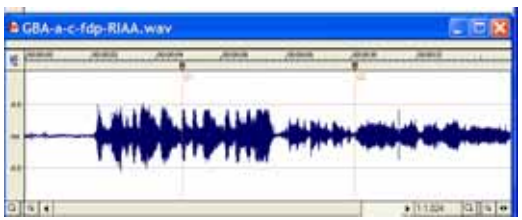
Width across
groove bottom



Measure slope
at each point
(stylus velocity)

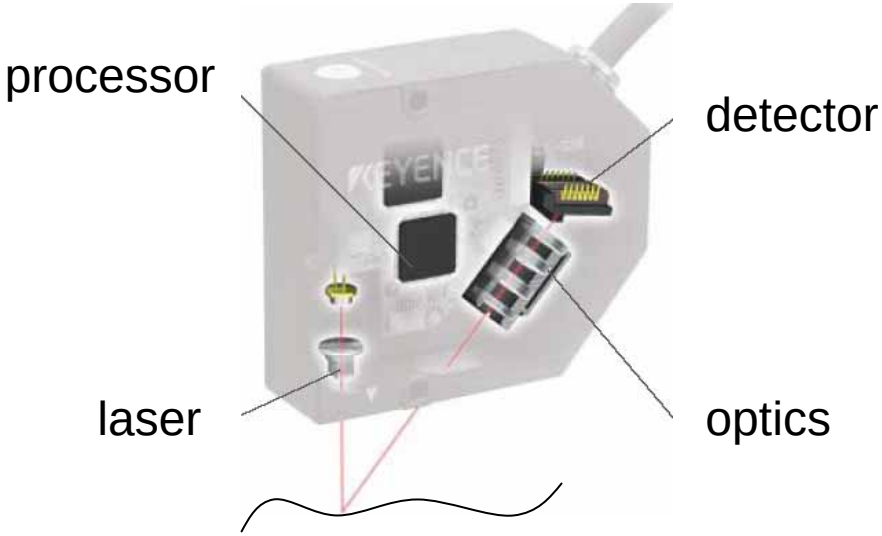


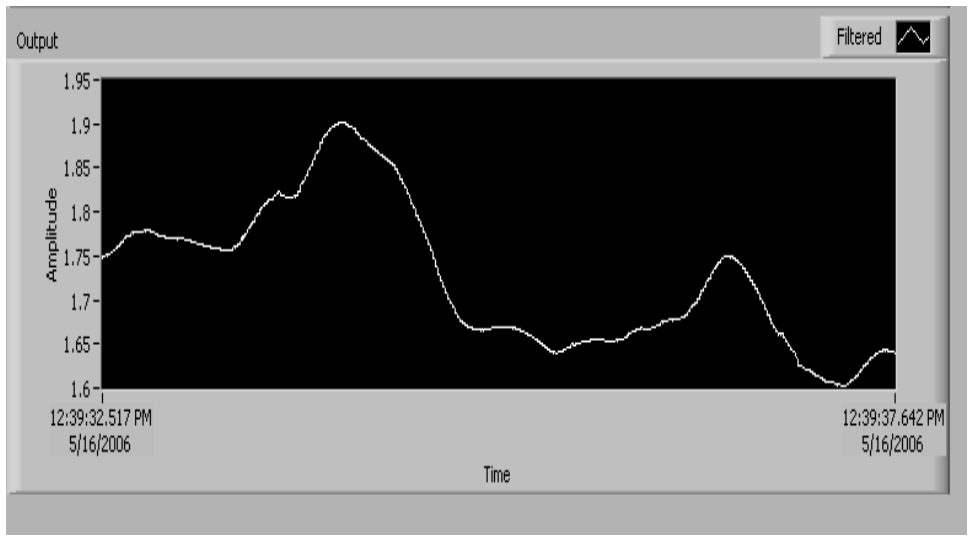




Average
Filter using width cut

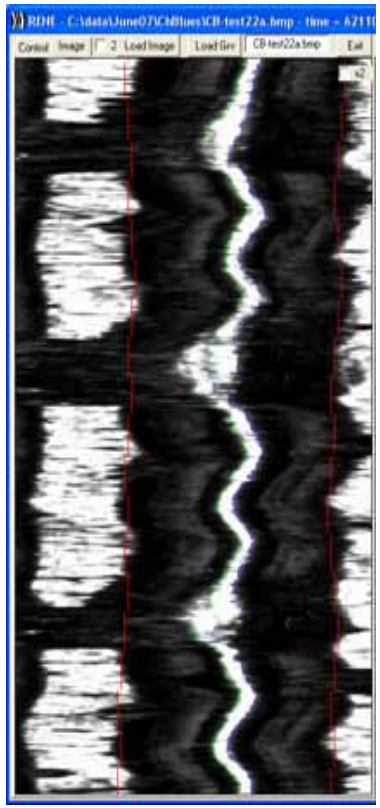
Adobe
C.Haber


processor
detector
laser
optics

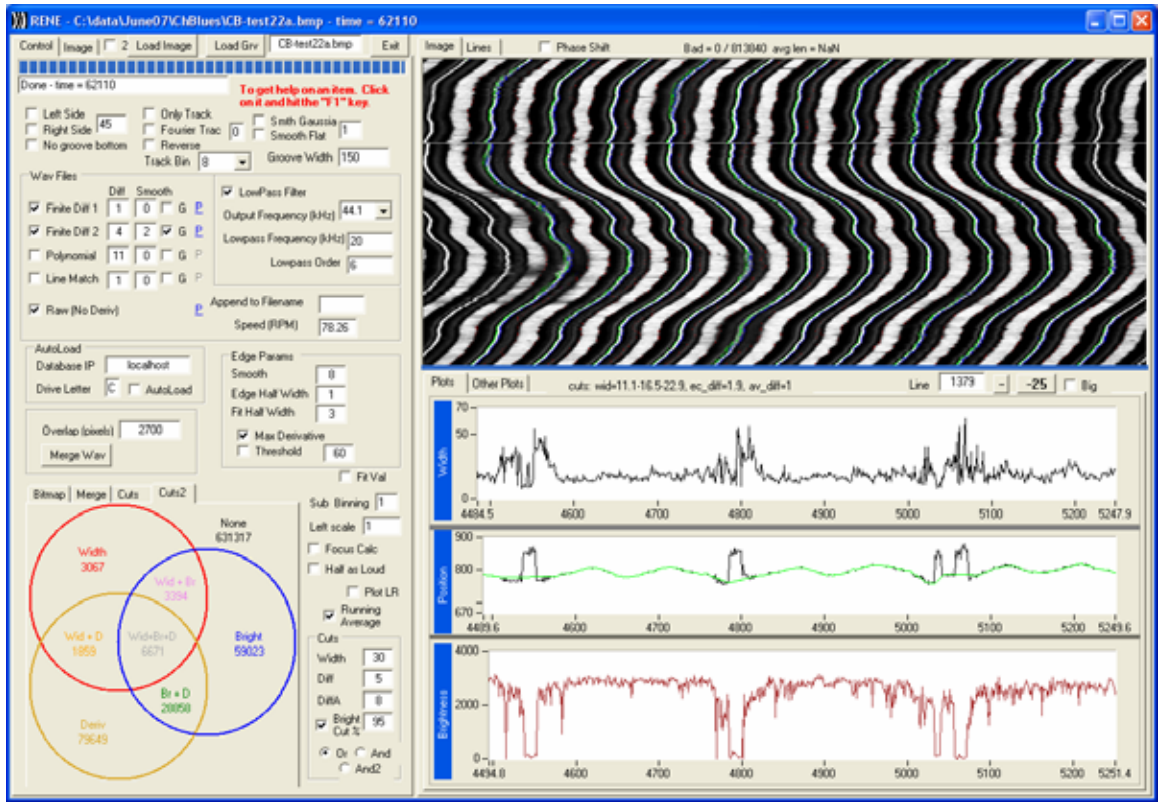

Output
Filtered
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
Amplitude
12:39:32.517 PM
5/16/2006
12:39:37.642 PM
5/16/2006
Time

Example of IRENE Software

Image View

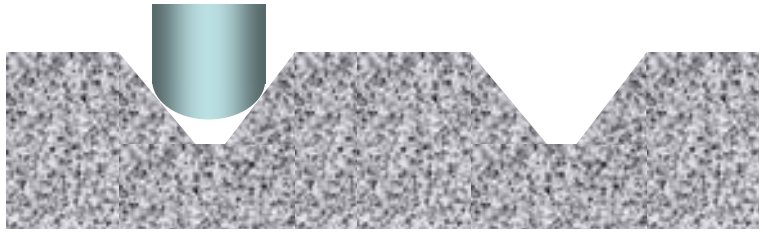


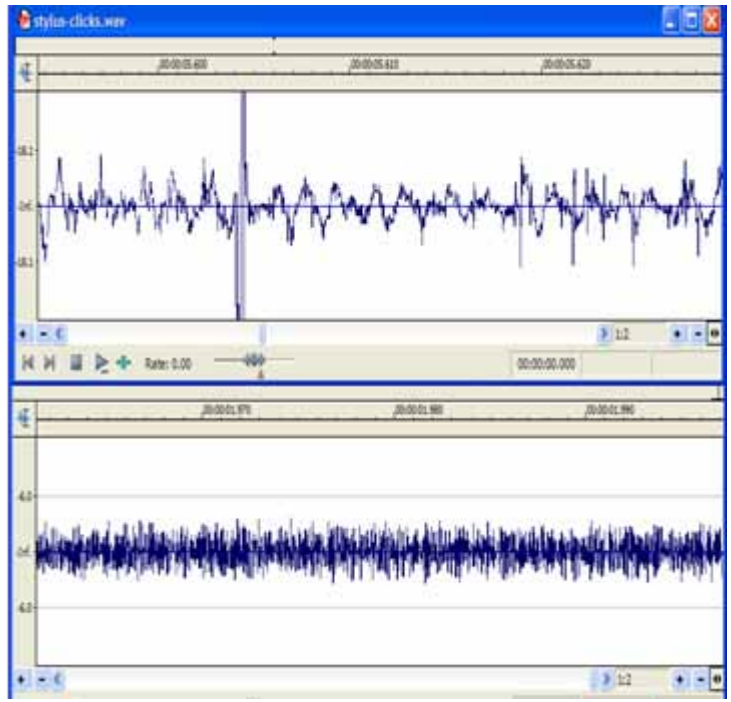
Control View



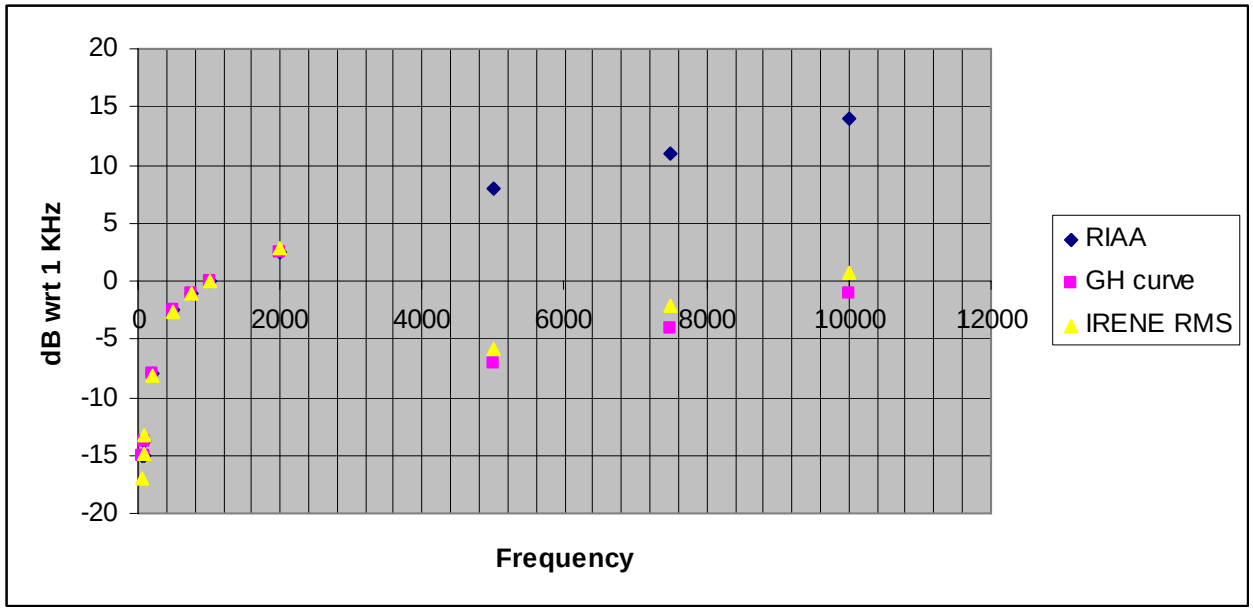
Sources of Noise

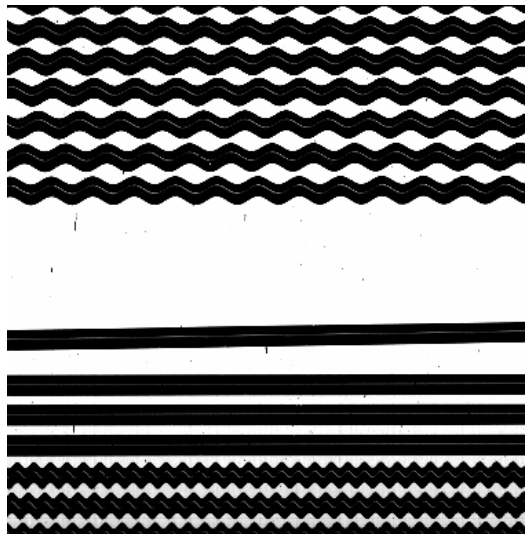
- Noise = random fluctuations in a signal
- Characterized by
  - Origin
  - Time structure, Amplitude
- Impulse noise (clicks)
  - Due to: scratches, debris
  - Rare, large amplitude
- Crackle
  - Due to: stylus wear
  - Frequent, moderate amplitude
- Broad band noise (hiss)
  - Due to: fine texture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





Test Discs





Pristine new acetate disc scanned by IRENE

Double Check Stomp

Duke Ellington, 1930

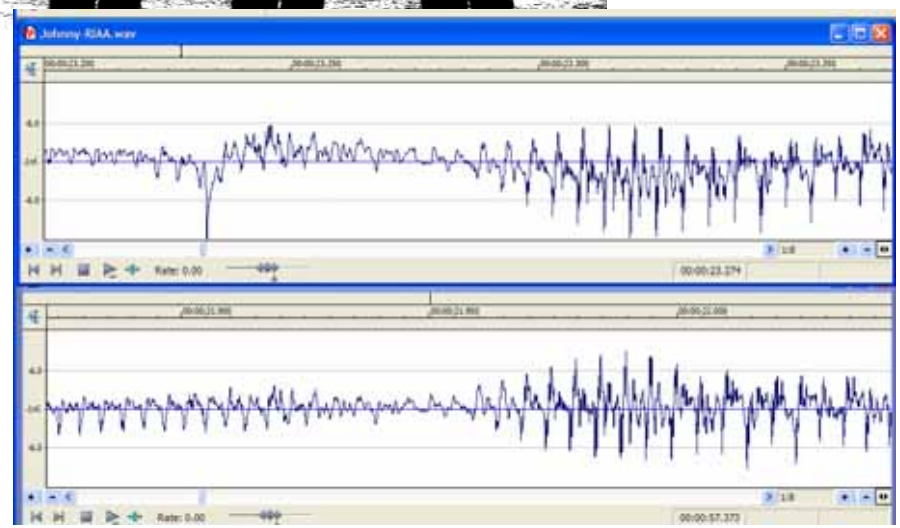
Comparison: Shellac disc in good condition, disc cleaned before stylus transfer, IRENE transfer before cleaning

Stylus, optimized, cleaned

IRENE
Not cleaned

“Johnny”: Les Paul and Mary Ford

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



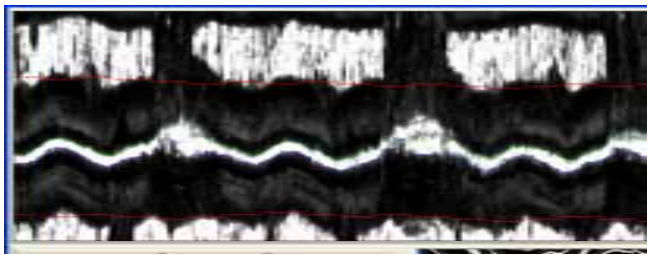
Stylus version has a clear skip due to scratch

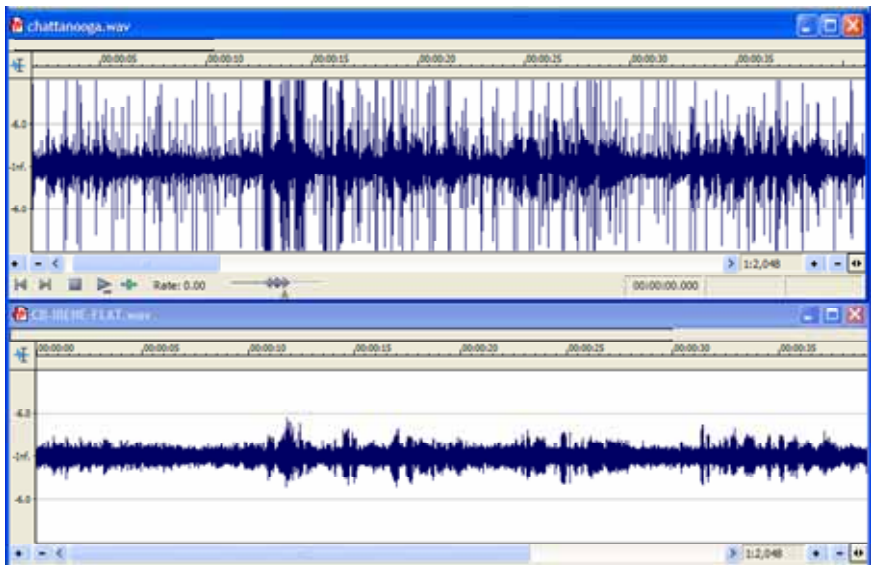
IRENE

Chattanooga Blues 1923

Ida Cox, Paramount 12063

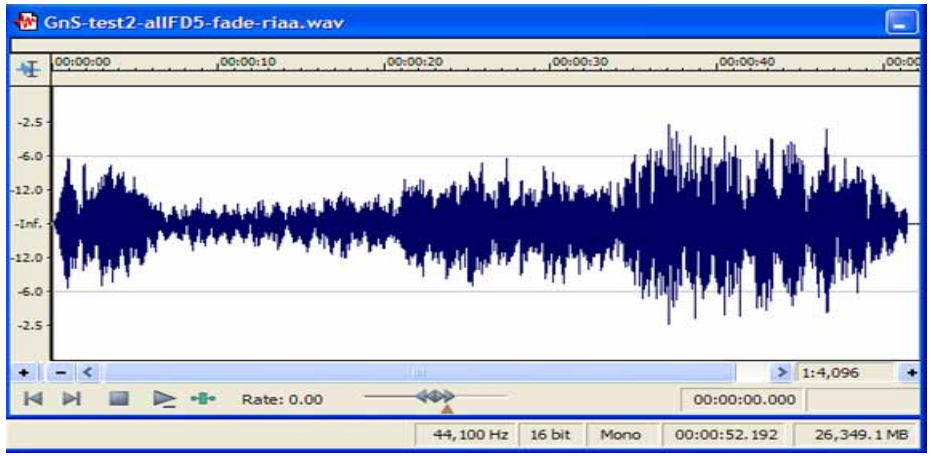
Acoustic recording, heavily worn, cracked, with significant stylus damage and distortion

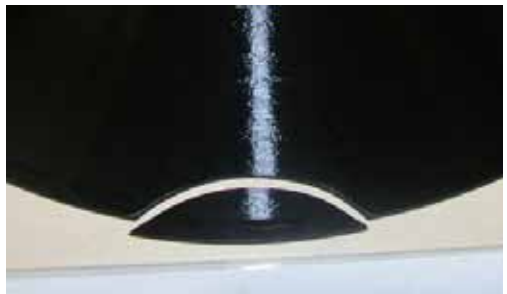


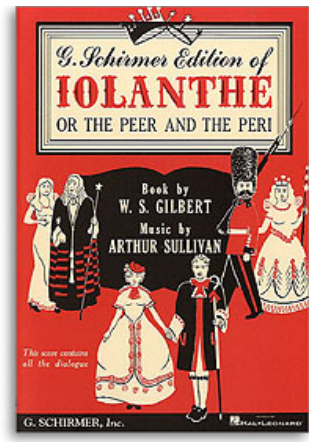


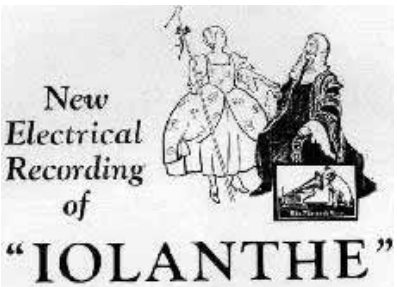
Broken Record

Gilbert and Sullivan "Iolanthe" 1930 Victor 9708







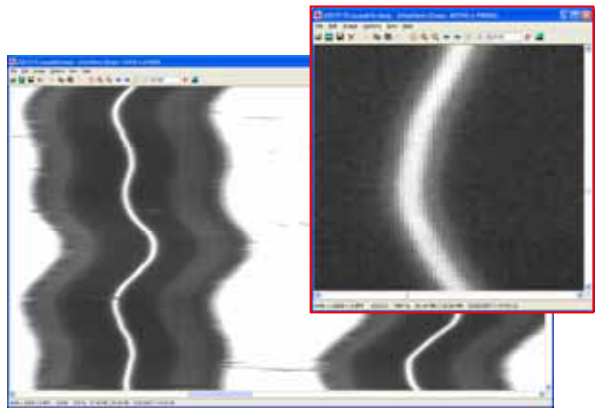


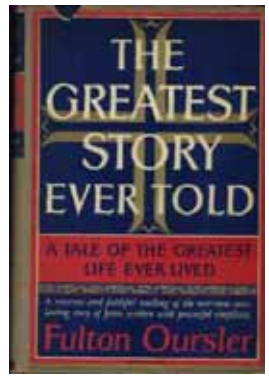
Lacquer Transcription Discs

Stylus

IRENE

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





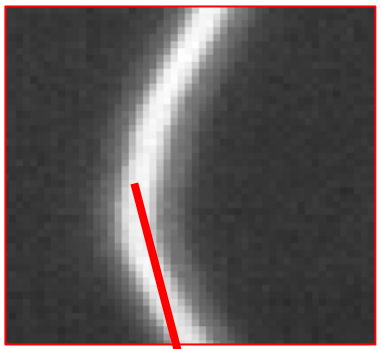
Stylus

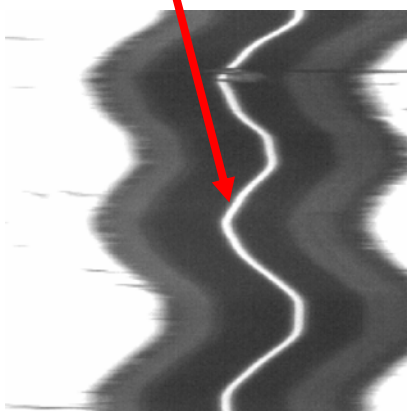
IRENE

1947 Studio "take"
Mutt Carey and his NY'rs
Shim-Me-Sha-Wabble

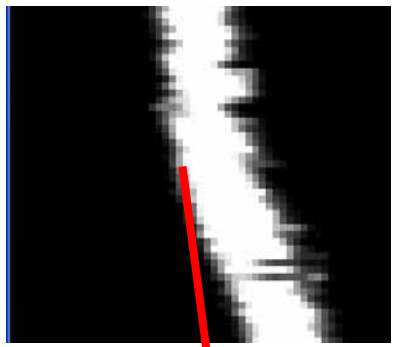
Media Characteristics

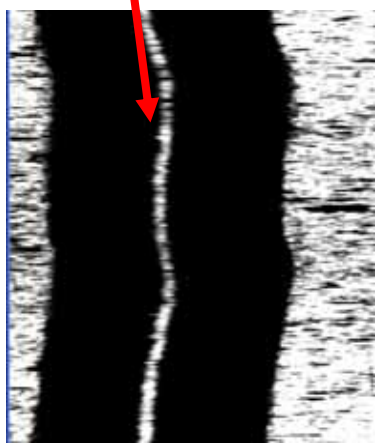
lacquer





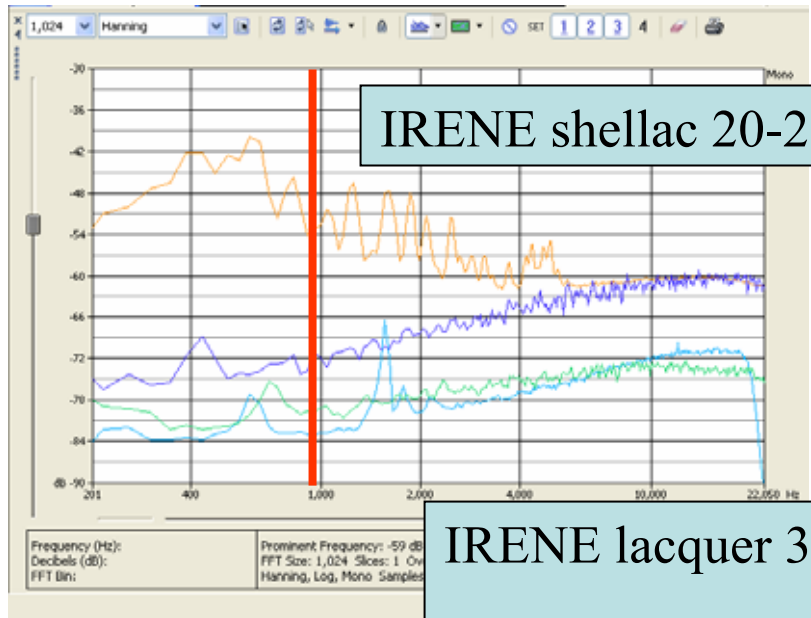
shellac





Signal and noise @ 1 KHz

IRENE audio



IRENE shellac 20-25 dB

IRENE lacquer 34 dB

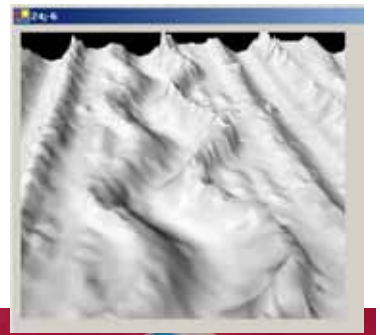
Stylus shellac 30 dB

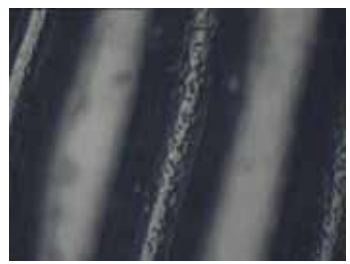
IRENE: Outlook

- Considerable insight into 2D optical scanning on a wide range of materials
- Particular performance on damaged media
- Good frequency response
- 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 may be expected
- Key hardware aspects were focus and illumination – still evolving
- Work underway to make IRENE a tool for the archive

3D Media

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

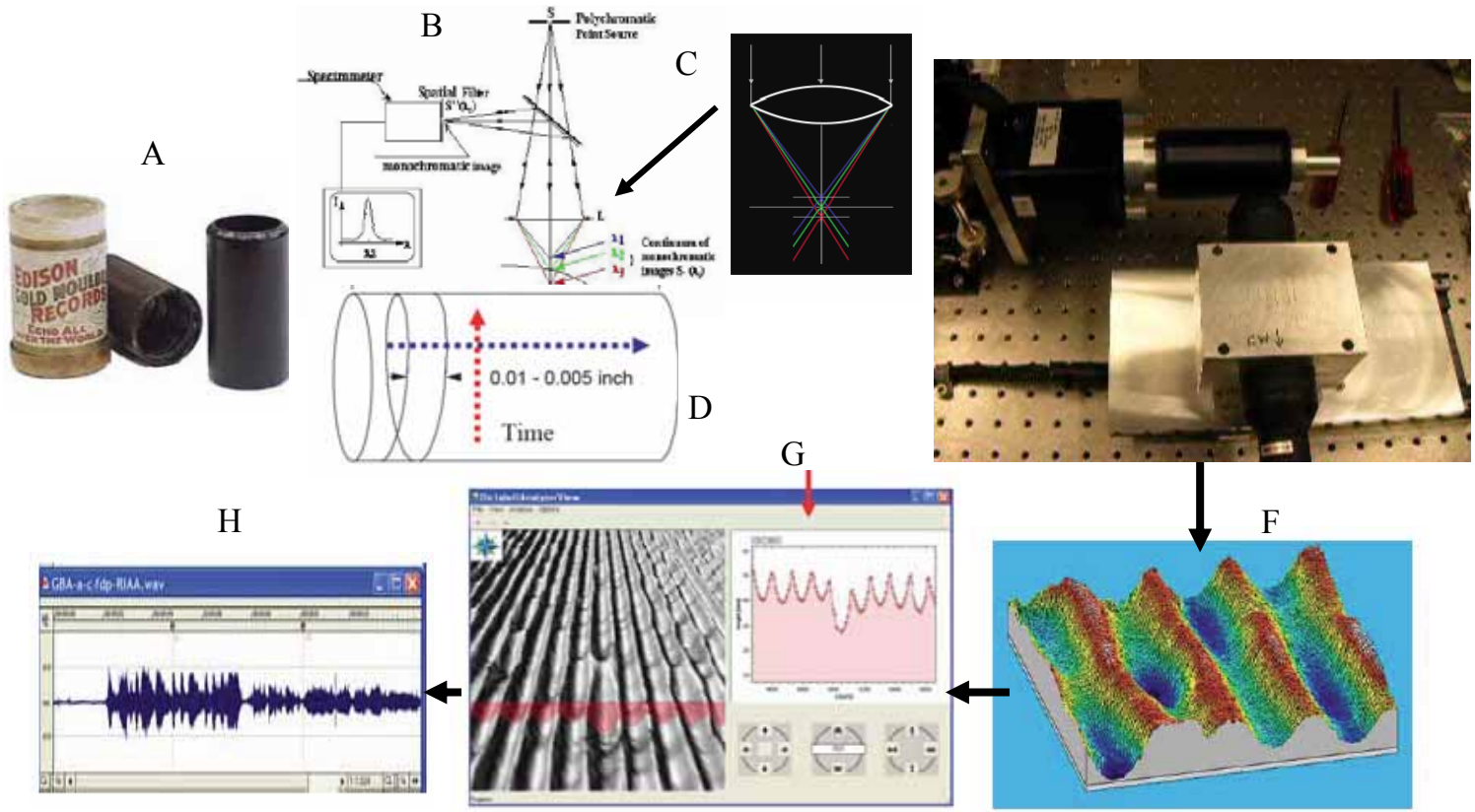


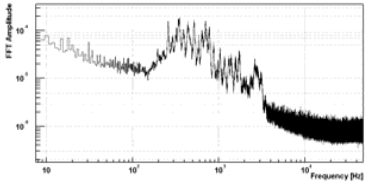


3D Scanner Project

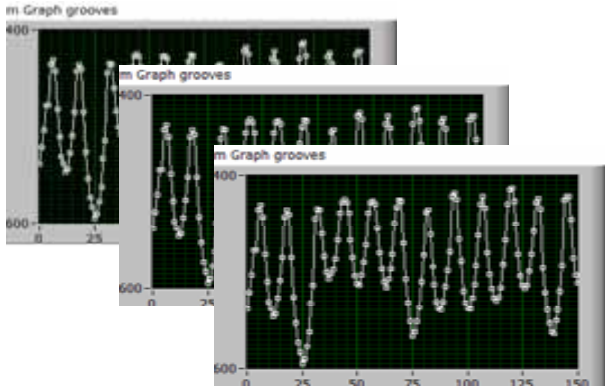
- Funded 10/07 by IMLS
- Based upon LC supported R&D
- Build fast scanner using new 180 point confocal probes
- Integrate into a friendly and robust control and analysis system.
- Evaluation program at the Library of Congress in 2009

3D Scanning Process

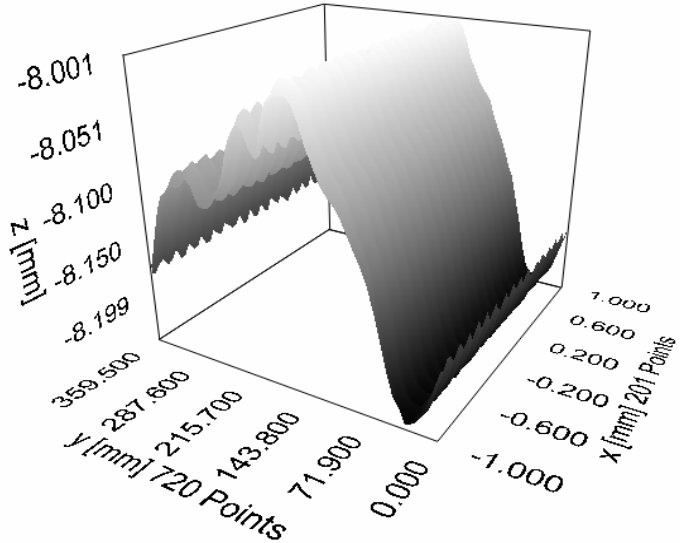




Sample at 96KHz to minimize effect of aliasing



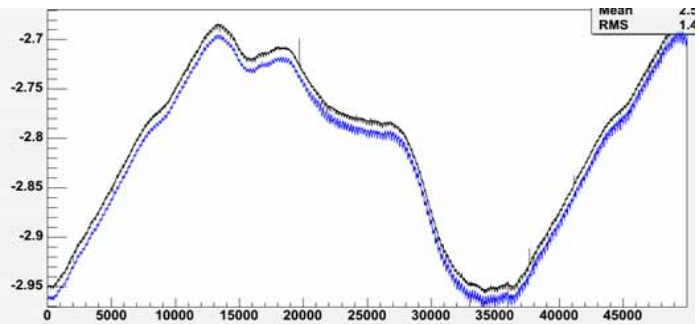
Sequential axial scans



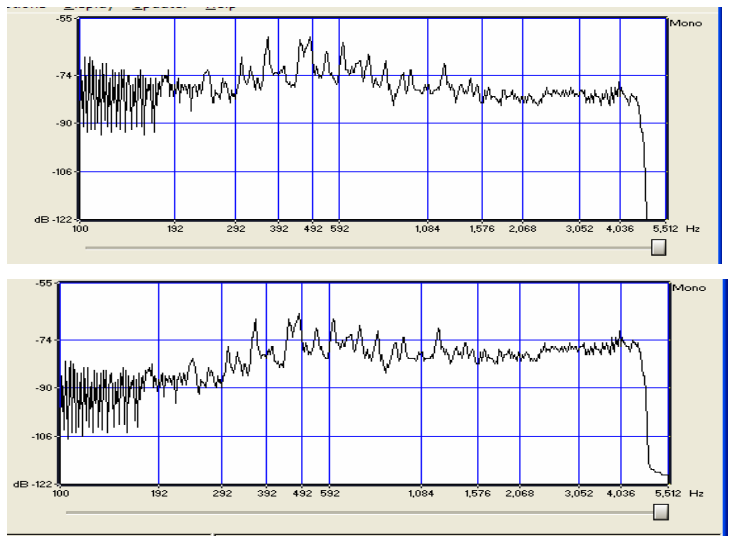
Subtract valleys from ridges to correct for overall shape

(Ridges provide (approx), geometrical reference)

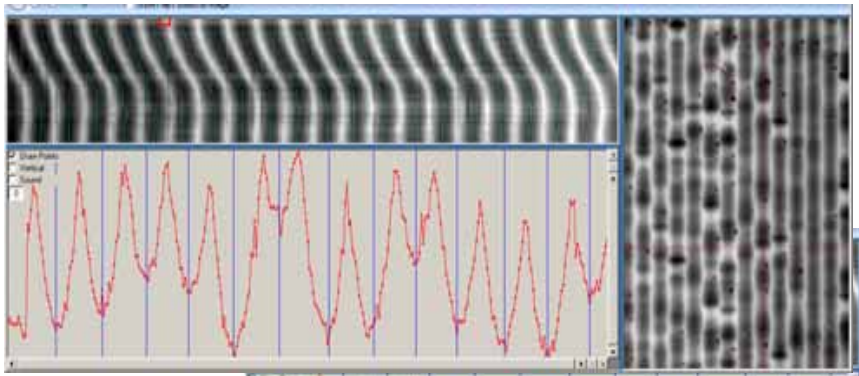
Overall cylinder shape due to off-center, deformation, heard as low freq rumble



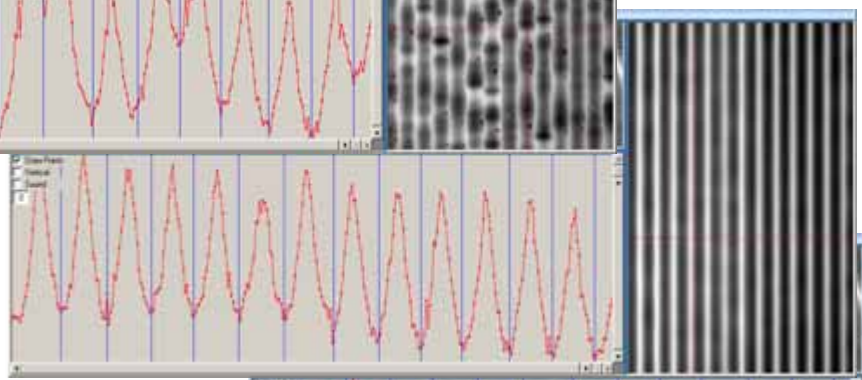
d/dt



3D Data Analysis

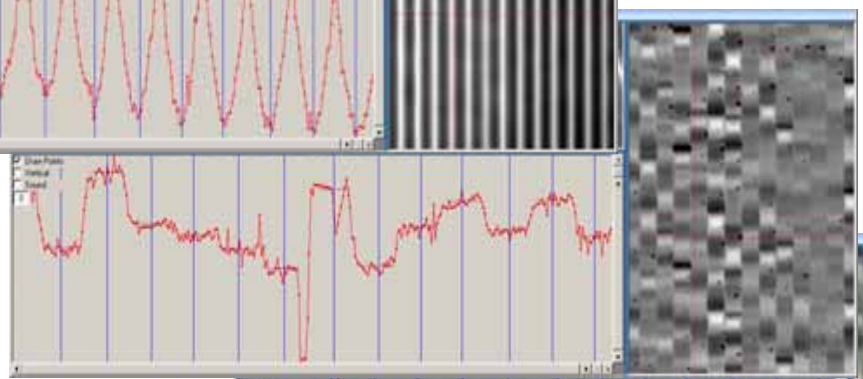


Raw image, greyscale = depth

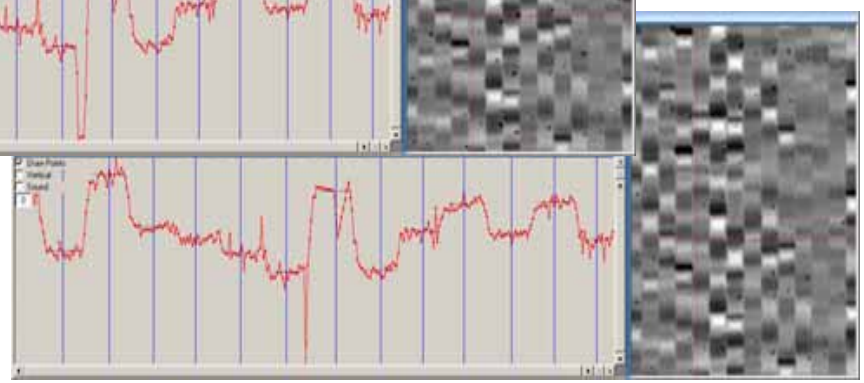


Spatial average to determine local shape

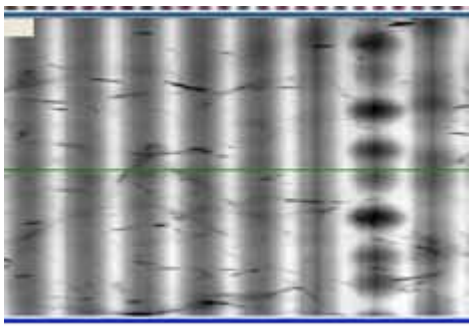
Profile view



Subtract local shape

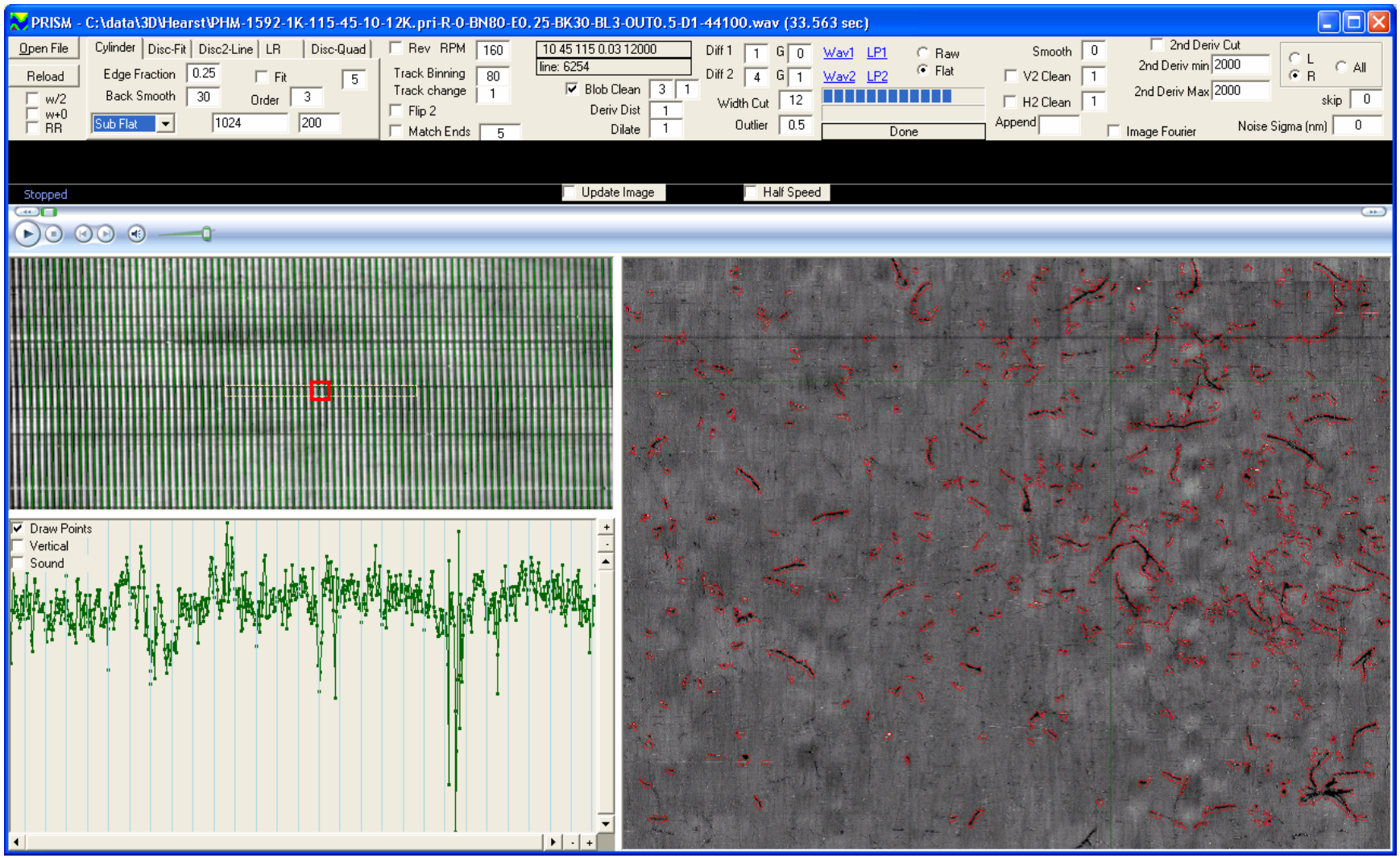


"blobs" removed

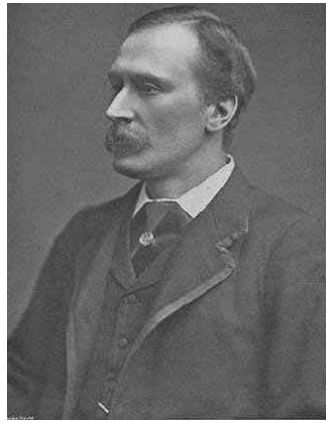


Condition assessment

Blob Finding



Sound Comparison

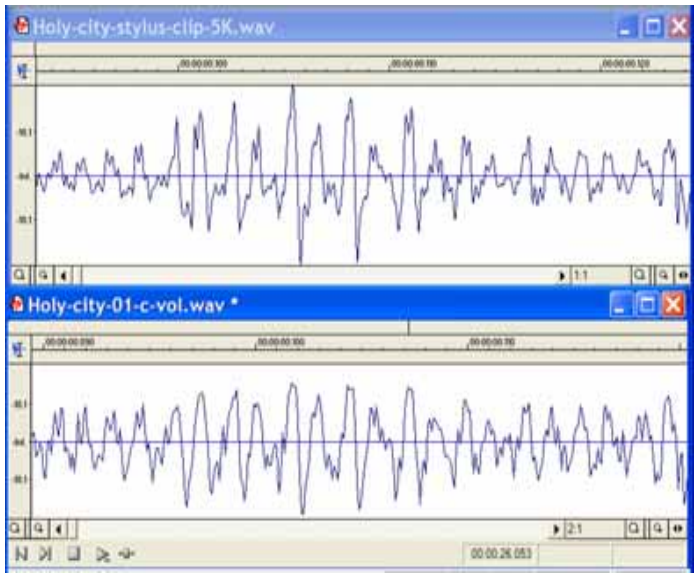


- The Holy City, composed by Stephen Adams,

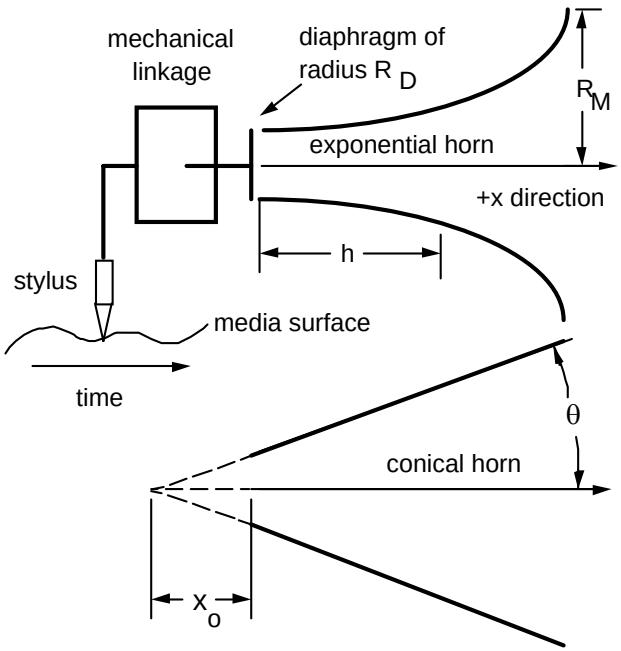
  The Edison and Skedden Mixed Quartet, Amberol 1601

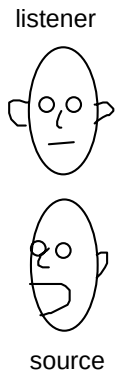
  Commercial cellulose release

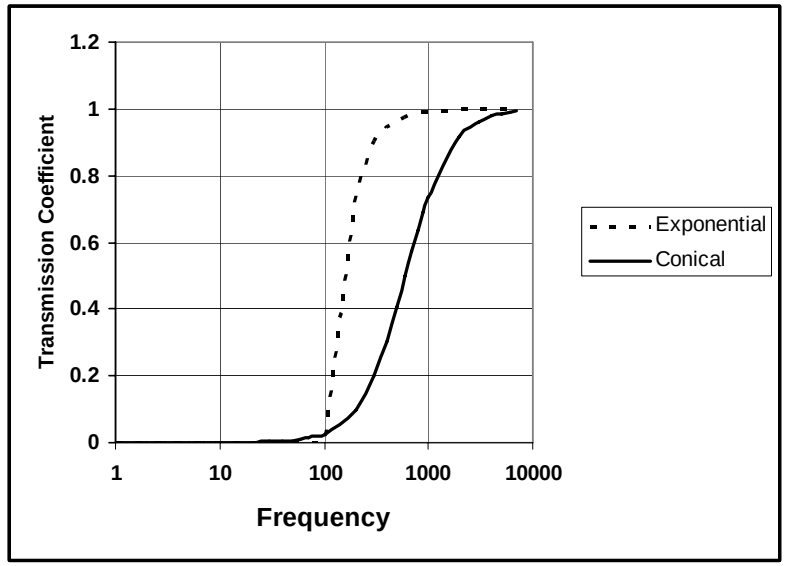
- Stylus
- Optical
- Optical + filter + EQ



Optical + EQ + filter



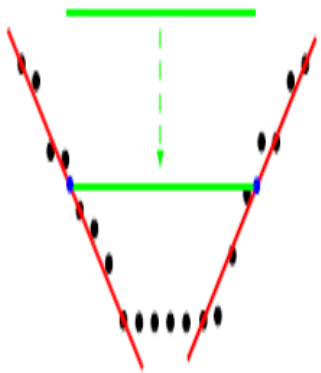


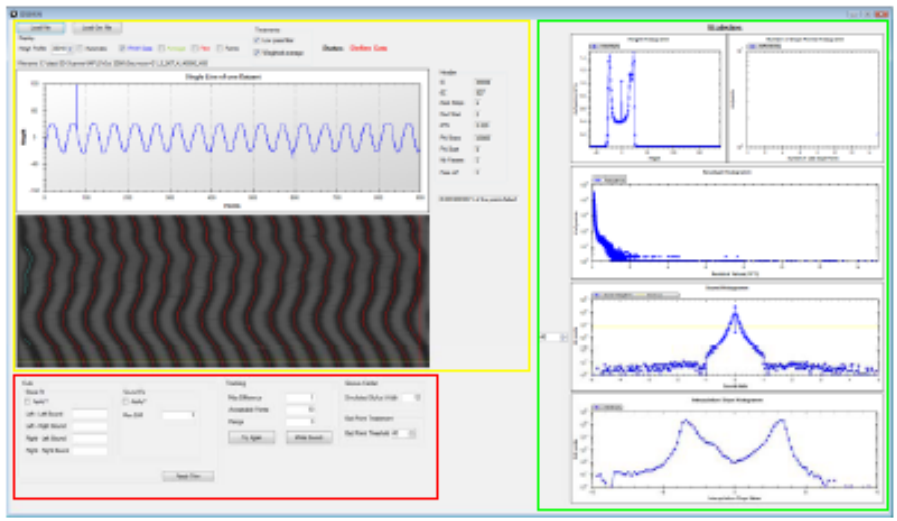


Response of horn and diaphragm at low frequency can modify response and deviations from "constant velocity" characteristic.

Application to Disc Scanning

- In principle the greater redundancy of 3D should improve disc data beyond the 2D IRENE method
- Current focus of effort in our lab
- Develop effective analysis and data reduction tools





Special Studies

- Both IRENE and 3D have attracted interest from institutions and individuals with particular items to transfer
- Rare lacquer transcription discs
  - Elvis, Janis, Theos Bernard
- Fieldwork and dictation cylinders
  - Jack London, Native American
- Dictation belts
  - Presidential history
- Early history of recorded sound

Rare Lacquer Transcription Discs

Typically these are one-of-a-kind and considered delicate. Archivists may prefer a non-invasive approach to playback and/or evaluation.

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.

Associated Press

Theos Bernard

Oriental Philosophy from Colum-

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

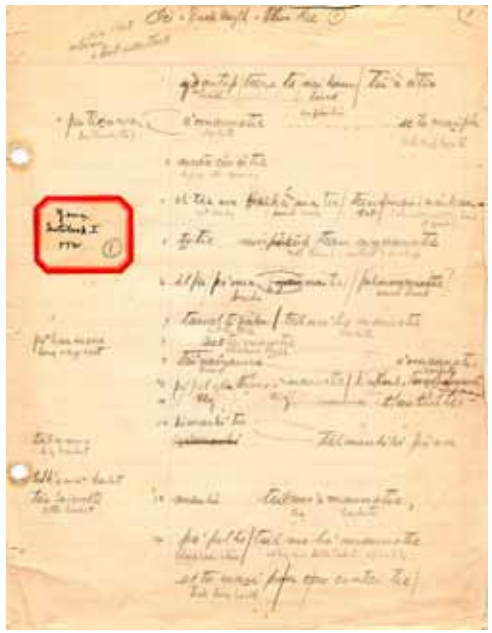
Personal messages….vending machines

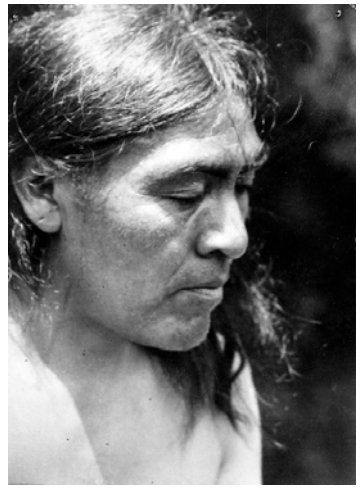
Hearst Collection Pilot Study

- 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.

Ishi Recordings: The Story of Wood Duck

Sam Batwai, Alfred L. Kroeber, and Ishi





This narrative is ~2.5 hours long and is contained upon 51 wax cylinders

Recorded and translated by Prof. T.T. Waterman

Clip from 3D pilot study

California State Park Cylinders

Page 1524 JL, Letters Vol 3
To Maximilian Ehrmann
Glen Ellen, California
December 2, 1915

Dear Max Ehrmann:

Just a rush letter, ere I sail for Hawaii. I merely want to tell you that everything concerning California prisons in the Star Rover is true. Ed. Morell is a real man, and Ed. Morell is his real name. He had a fifty year sentence, and he spent five years of it in solitary, as I have described. Two years ago Jake Oppenheimer was executed in California for assault and battery. I can only repeat, that what I have described is true of California up to the year 1913. I do not know what has happened in California since that date.

If you ever read a book of mine entitled The Road, in which I give some few of my experiences, you will notice that in the Erie County penitentiary at Buffalo, New York, I have slipped by without describing much of the worst that I found obtaining there. What I found there was unprintable, and almost unthinkable.

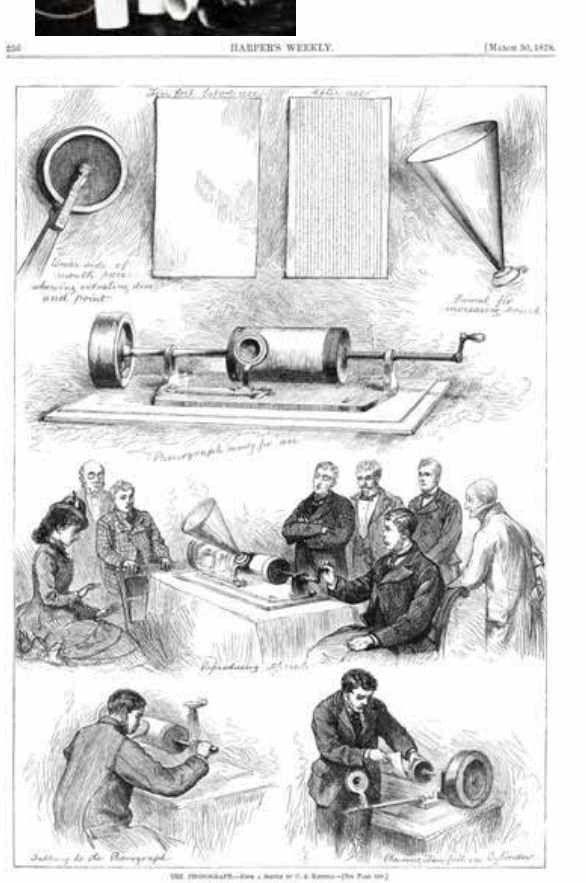
I am still curious to know how my handling of the Christ situation in Jerusalem will strike you.

Sincerely yours,

Early Recorded Sound

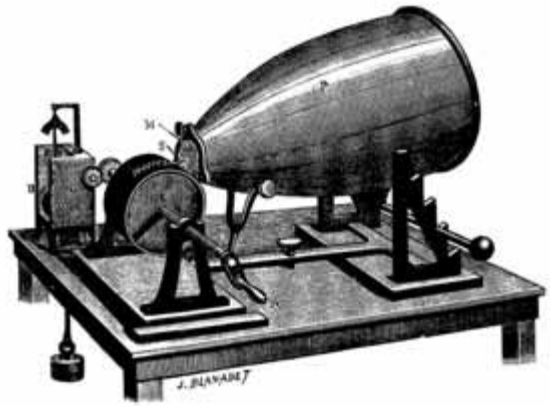
Phonograph
Tom Edison
1877

Phonautograph
Leon Scott
1853

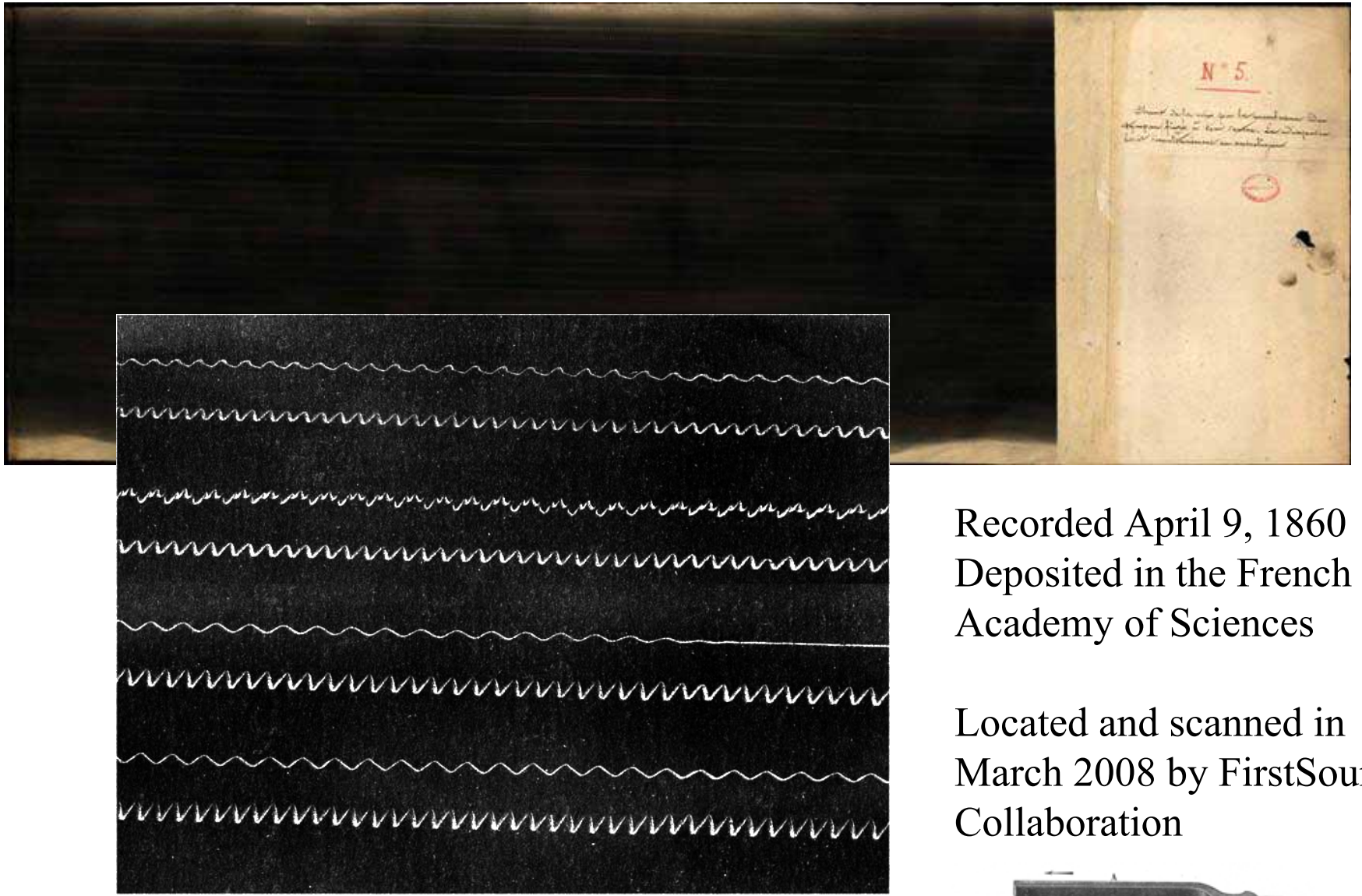


Scott enscribed sound on paper and could not play it back

Edison embossed sound on foil and was therefore the first to reproduce it.

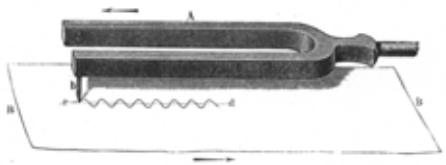


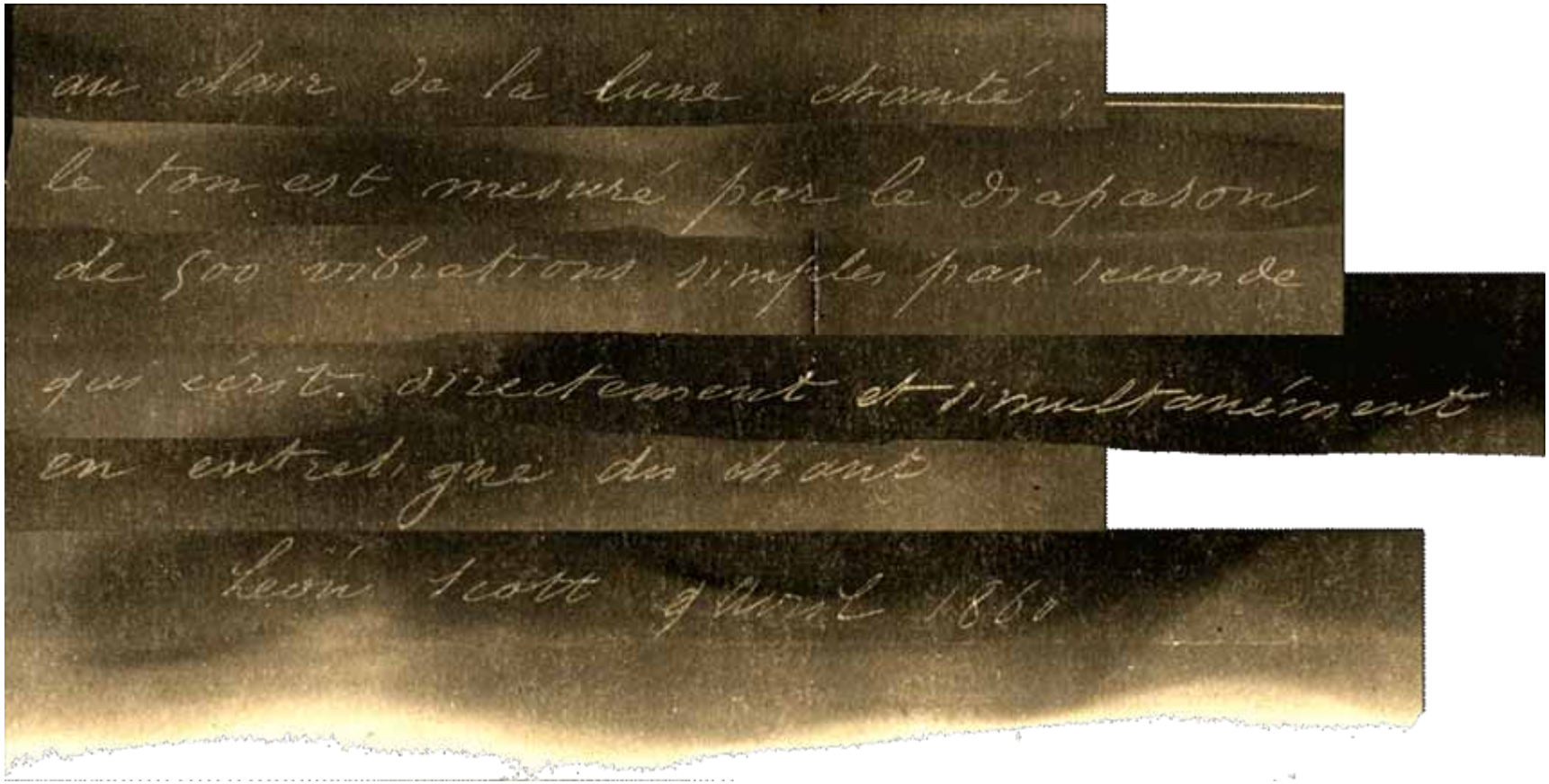
Paper coated with lamp soot (lamp black)



Recorded April 9, 1860
Deposited in the French Academy of Sciences

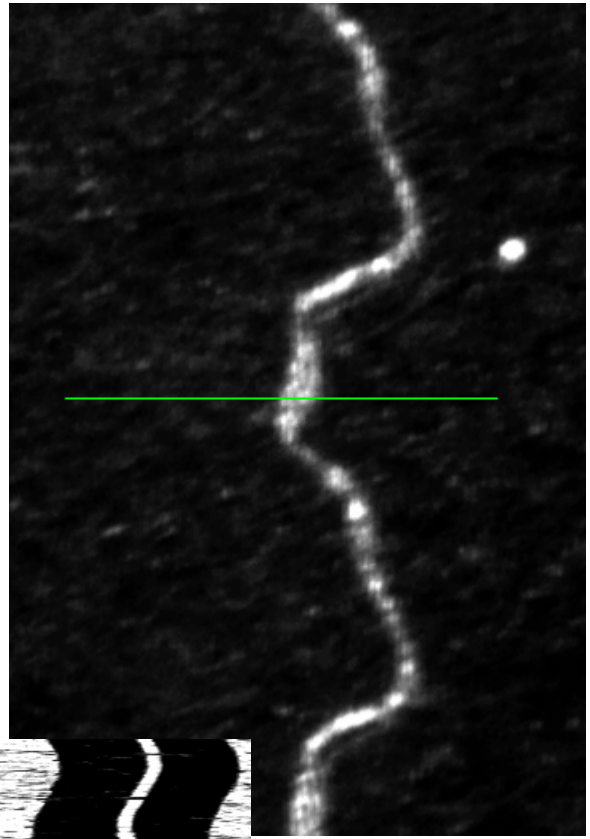
Located and scanned in March 2008 by FirstSounds Collaboration

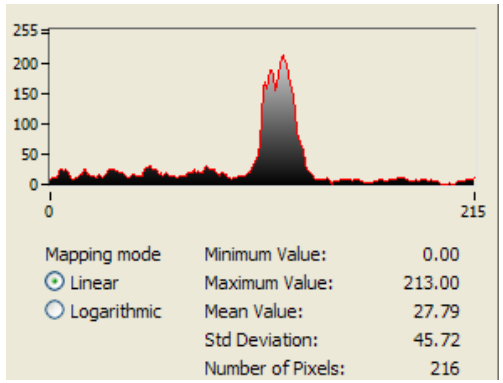


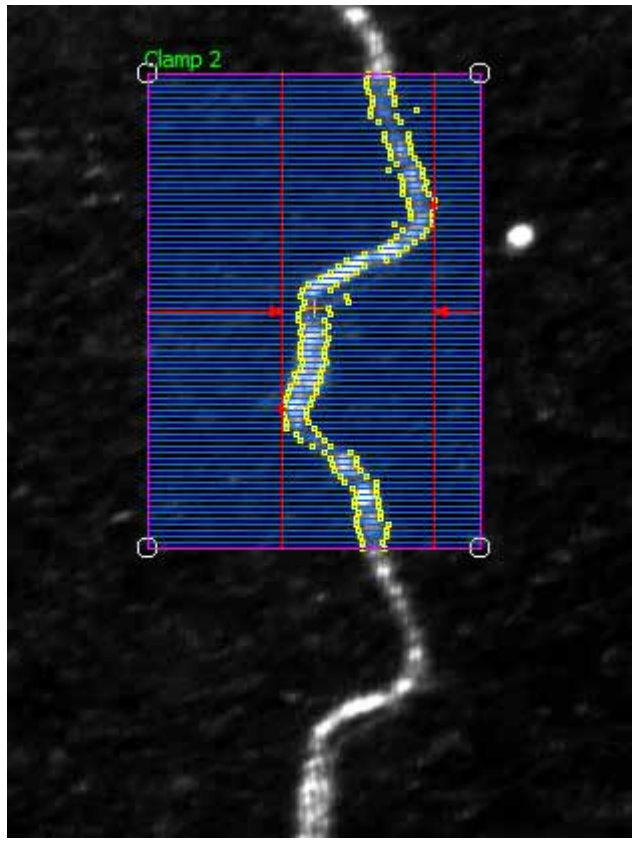


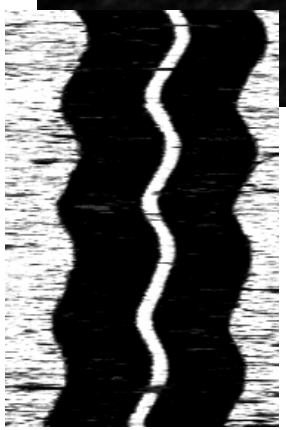
"Au Clair de la Lune" ["By the Light of the Moon"] sung;
"…the pitch is measured by the tuning fork of 500 simple vibrations per second which writes directly and simultaneously in interlinear space of the song"

Léon Scott 9 April 1860









Phonautograms are visually similar to “IRENE” 2D scans and can therefore be processed and analyzed by the same tools…
…albeit with much lower fidelity.

1st example of a sound recording in history

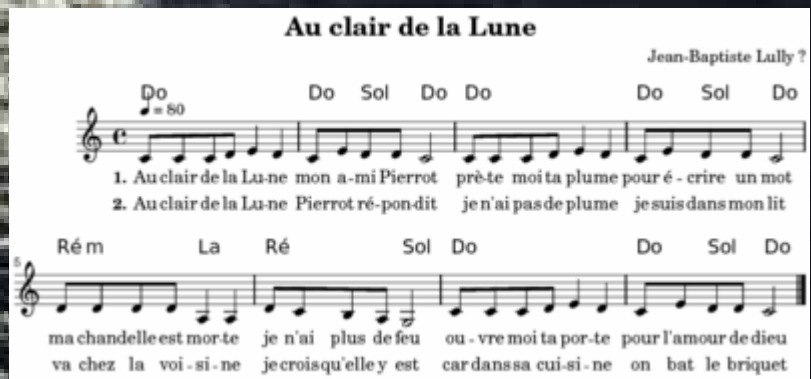
Au clair de la lune, mon ami Pierrot
Prête-moi ta plume, pour écrire un mot.
Ma chandelle est morte, je n'ai plus de feu.
Ouvre-moi ta porte, pour l'amour de Dieu
Au clair de la lune, Pierrot répondit
Je n'ai pas de plume, je suis dans mon lit.
Va chez la voisine, je crois qu'elle y est
Car dans sa cuisine, on bat le briquet.

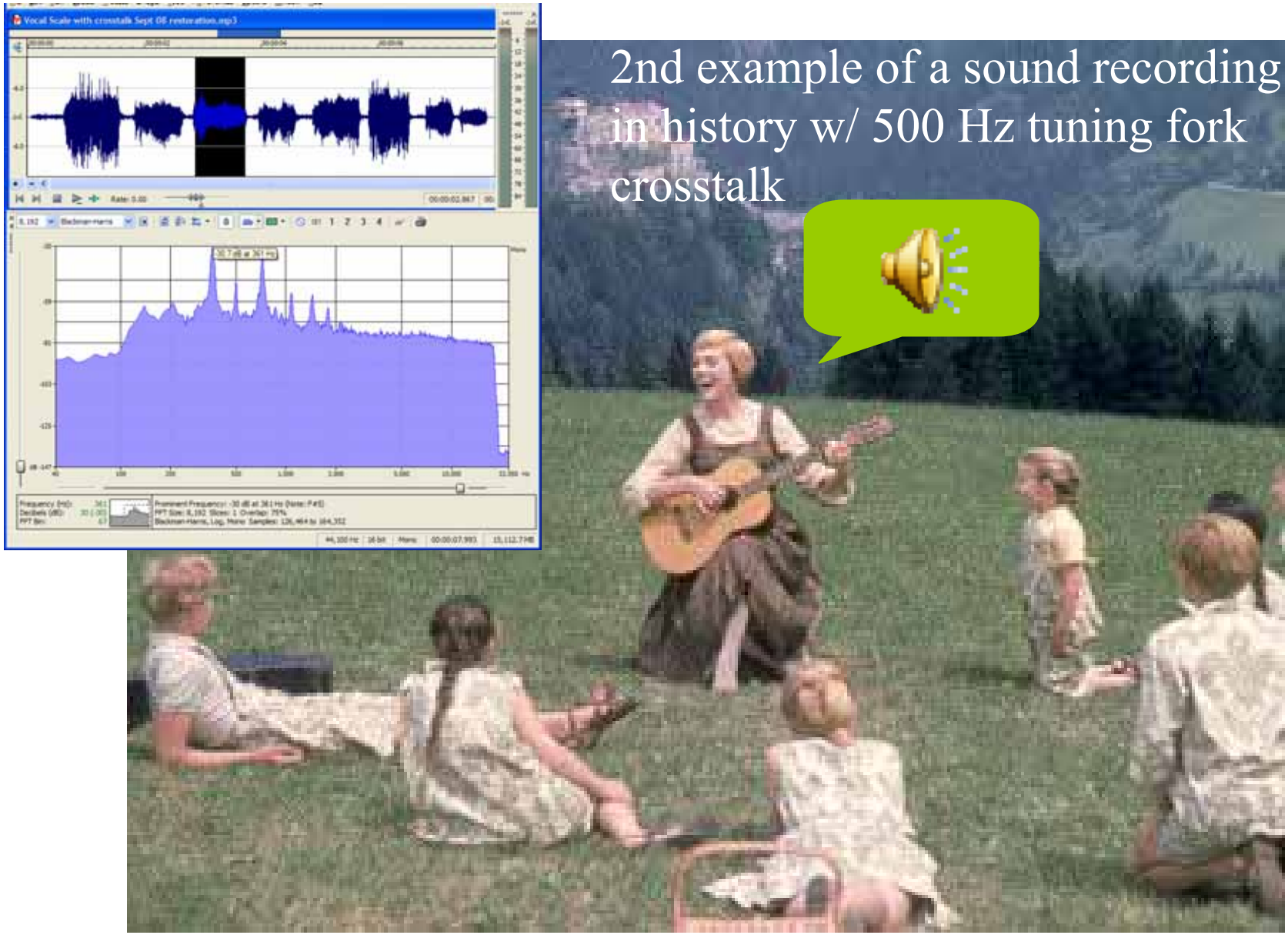
Under the moonlight, My friend Pierrot
Lend me your pen, So I could write a word
My candle is out, I've no more light
Open your door for me, For God's sake.
Under the moonlight, Pierrot replied,
I've no pen, I'm in my bed.
Go next door, I believe they're in,
For in the kitchen, Someone lit a match.

2008

1931

1860





2nd example of a sound recording in history w/ 500 Hz tuning fork crosstalk

Do Re Mi Fa So La Ti# Do ~D Dorian Mode with raised 6th

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
  - 12 undergraduates from EE, Comp Sci, and Physics
- Public presentations
  - ~60 seminars, radio, TV, newspapers, magazines, blogs, hundreds of Google hits and email inquiries.
- Research opportunities for students from groups under-represented in science and engineering

Morning Edition
July 18, 2007

npr

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HEALTH & SCIENCE

You Can Play the Record, but Don't Touch

Listen by Nell Greenfieldboyce

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Enlarge Nell Boyce, NPR

Peter Alyea, a digital conservation specialist at the Library of

Morning Edition, July 16, 2007 ·

At the Library of Congress, in a small, white room with bright red carpet, physicist Carl Haber sits down to play a record from 1930. It's a recording of Gilbert and Sullivar here's the s record is br

"It looks like hungry and

WEB RESOURCES

» A Presentation of IRENE, by Carl Haber
(Requires Adobe Acrobat)

» Sound Reproduction R & D Home Page

NY Times Page 1
March 27, 2008

HOME PAGE | MY TIMES | TODAY'S PAPER | VIDEO | MOST POPULAR | TIMES TOPICS

The New York Times

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Researchers Play Tune Recorded Before Edison

By JODY ROSEN
Published: March 27, 2008

For more than a century, since he captured the spoken words "Mary had a little lamb" on a sheet of tinfoil, Thomas Edison has been considered the father of recorded sound. But researchers say they have unearthed a recording of the human voice, made by a little-known Frenchman, that predates Edison's invention of the phonograph by nearly two decades.

Enlarge This Image The 10-second recording of a singer

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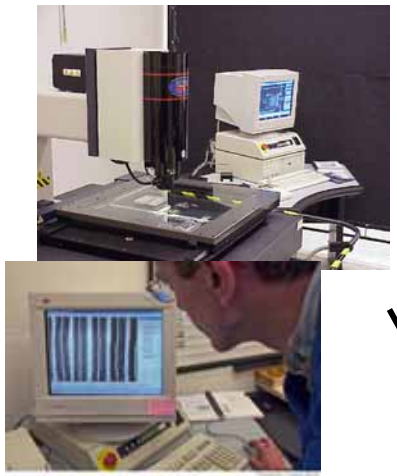
ARTICLE TOOLS SPONSORED BY
THE WRESTLER
NOW PLAYING

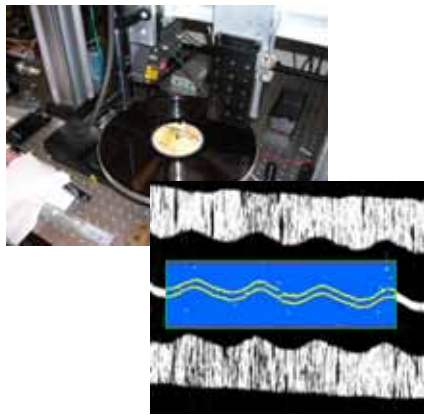
Optical Scanning: Technology Roadmap

Basic 2D concept demonstration
40 min / 1 sec



2002

2D disc R&D
4 sec / 1 sec



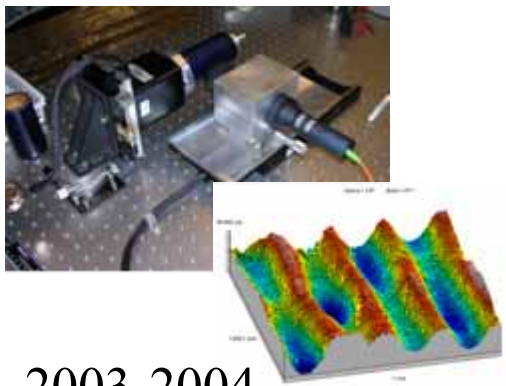
IRENE
System eval

2006-2007

Production mode discs

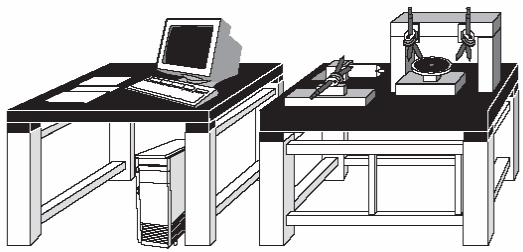
2009

3D cylinder R&D
20 hr / 1 min



2003-2004

3D System
10 min / 1 min

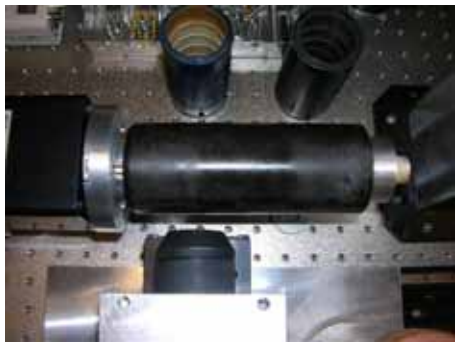


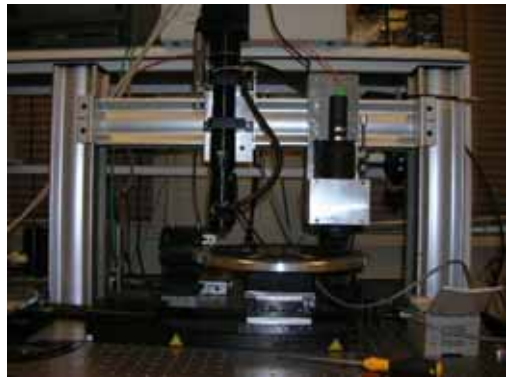
2008-2009

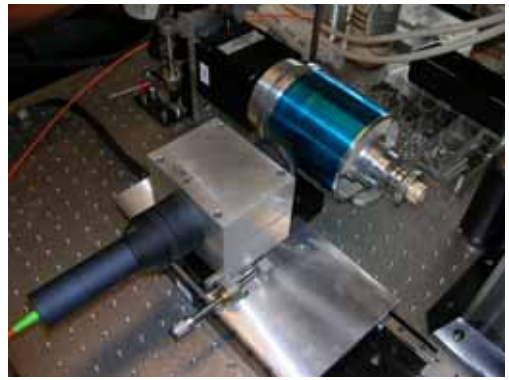
Pilot study

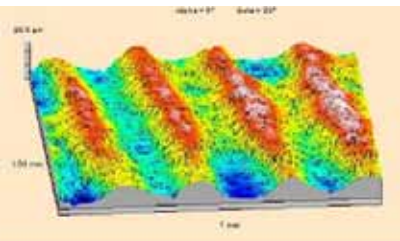
Web site: http://irene.lbl.gov/

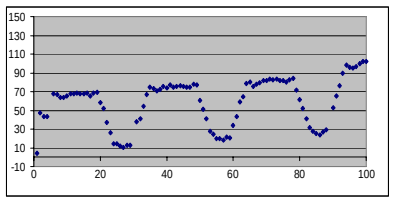
Optical Scanning: A general tool to preserve and create access to recorded sound history

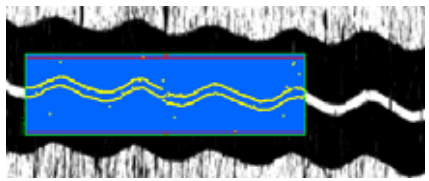












Wax cylinder

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).

Extra Slides

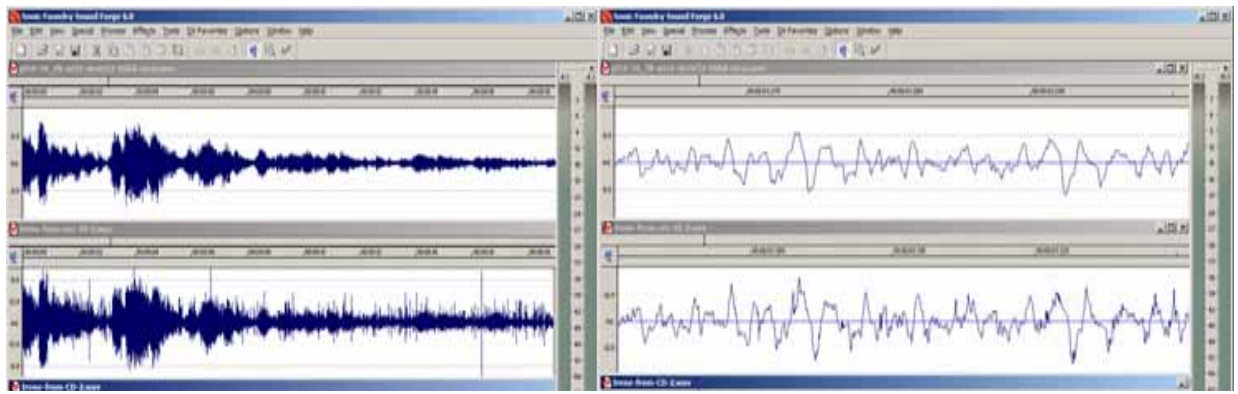
Early Sound Comparison 2002

"Goodnight Irene" by H. Ledbetter (Leadbelly) and J.Lomax, performed by The Weavers

with Gordon Jenkins and His Orchestra ~1950

optical readout.

mechanical (stylus)



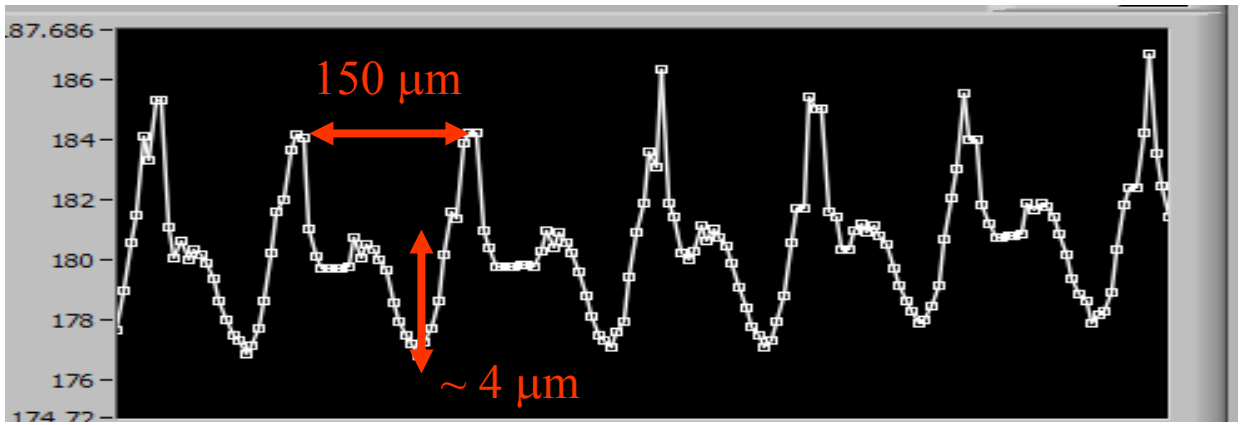
Plastic Dictation Belts

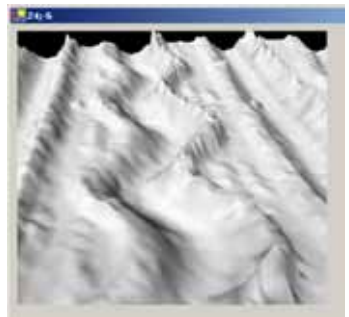
- These were used for dictation, telephone and radio monitoring 1940's-1970's
  - US Presidential phone conversations
  - Dallas PD Dictabelt 10
- NARA proposed 3D scanning of these artifacts for digital preservation and to create access.
- Groove is embossed, lateral modulation, shallow
- Never meant as an archival medium, poor storage

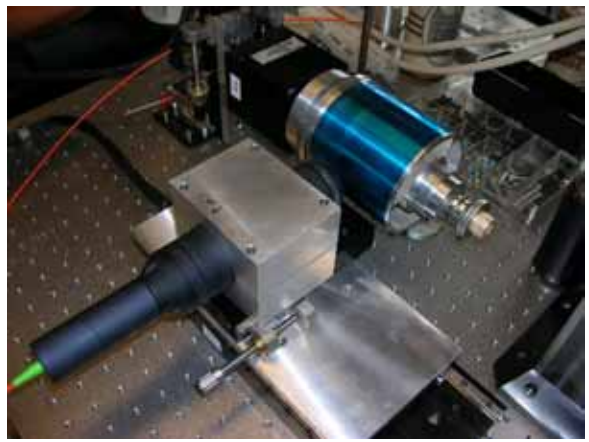
Dictabelt Scanning

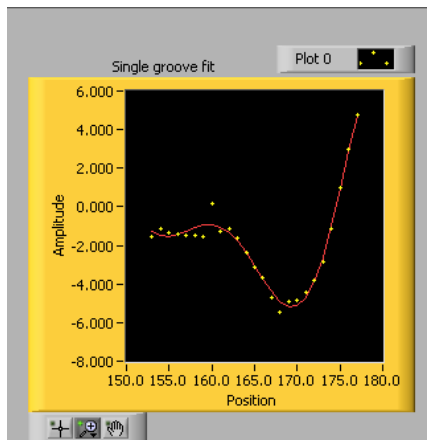
Pilot study performed and reported at request of NARA
Development of measurement methods, calibration, analysis software.

Dictation belt

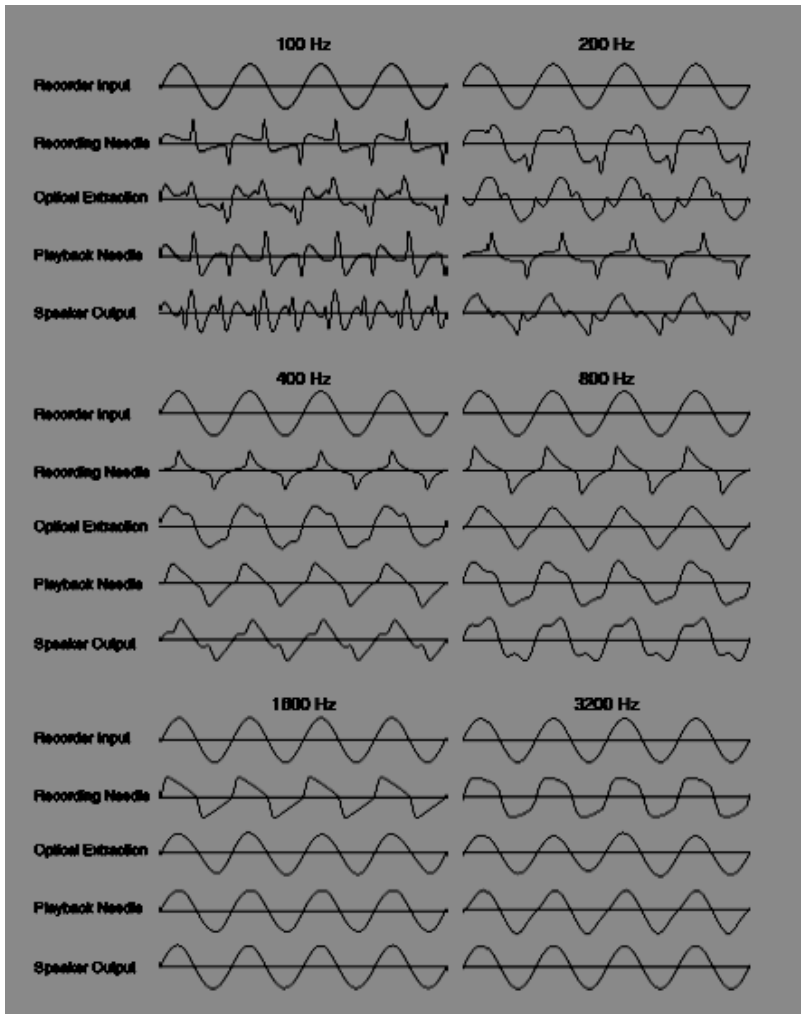


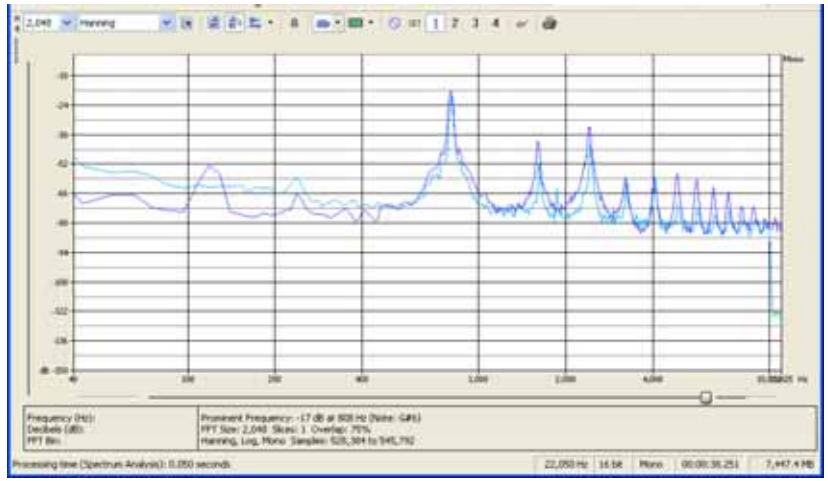


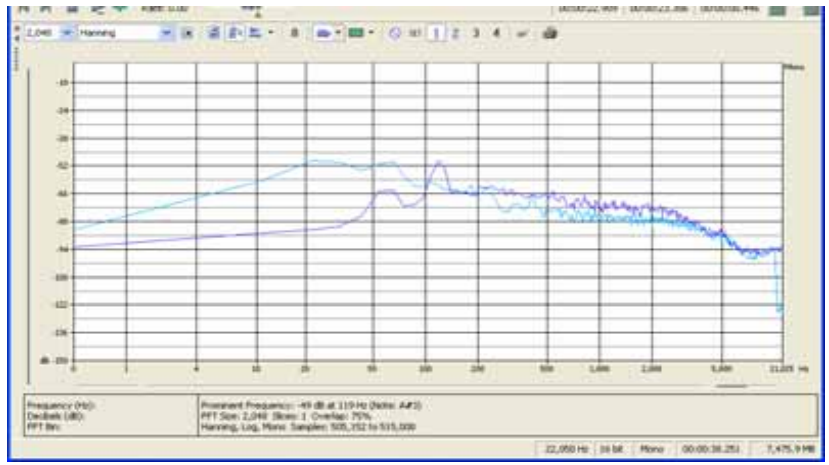




Study of test tone dictation belts







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