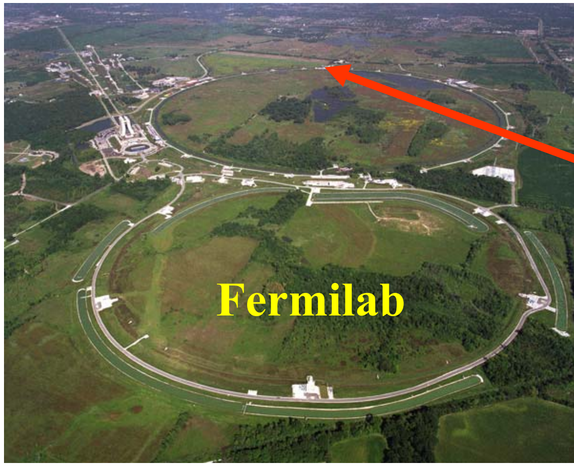
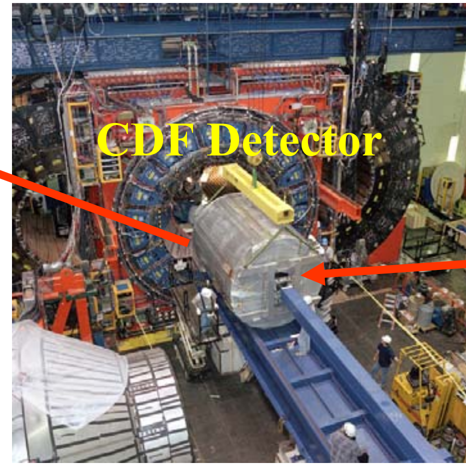
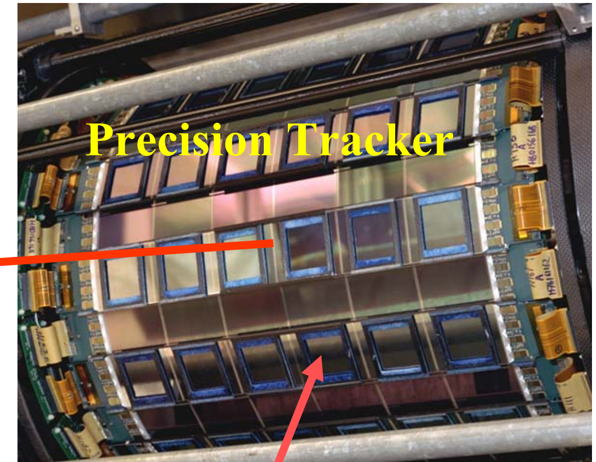
Imaging the Voices of the Past: Using Physics to Restore Early Sound Recordings

Particle Physics

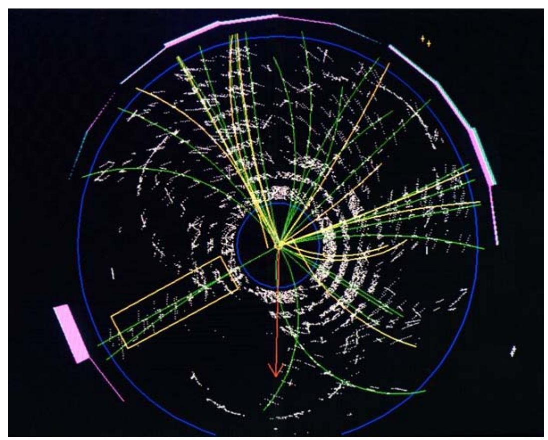
Basic study of matter & energy, re-create conditions of early universe.



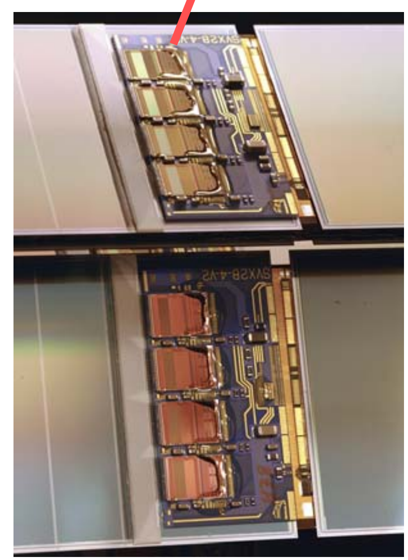




>Massive data collection and analysis
>Computerized pattern recognition to analyze signals and noise in detectors
>Precision mechanical survey methods used to fabricate sensor array

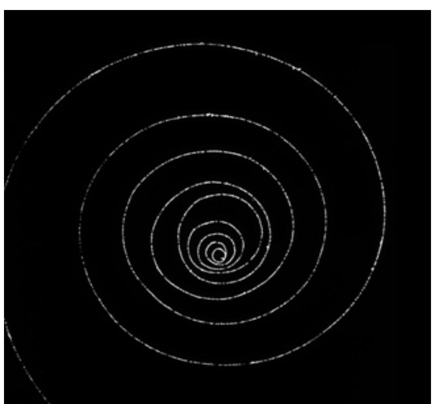


Computer event display



Berkeley Spiral Scanner circa 1970

Luis Alvarez
1968 Nobel Prize in Physics



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

Collaboration and Support

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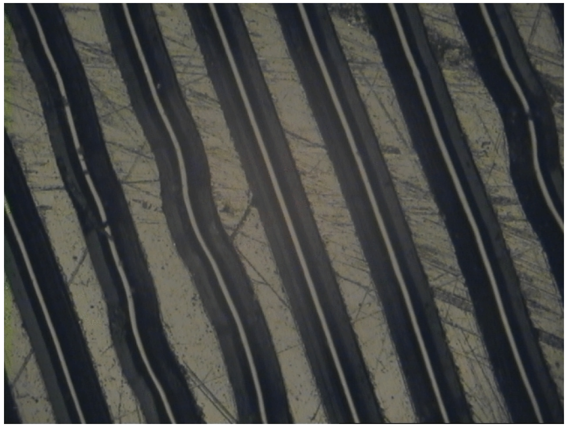
The Problems

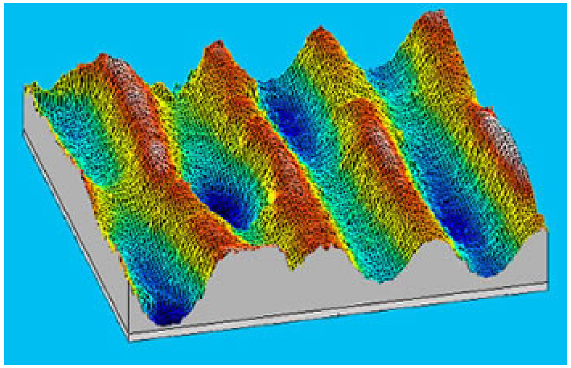
- Extensive historical sound collections exist worldwide
  - Damaged
  - Delicate
  - Decaying
  - Diverse
- Move towards large scale digitization of collections

Issues for Archives

- **Preservation:** safeguard artifacts to satisfy any conceivable future need.
  - Prioritized process
  - Do no harm
  - Highest quality
- **Access:** put entire collections into digital form to provide broad access to the public.
  - Mass processing required
  - Diverse media and condition
  - Moderate quality

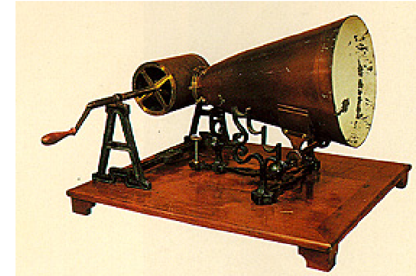
A Non-Contact Approach: Digital Imaging

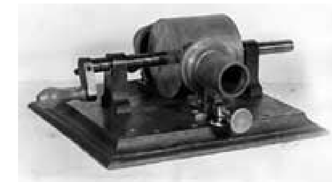




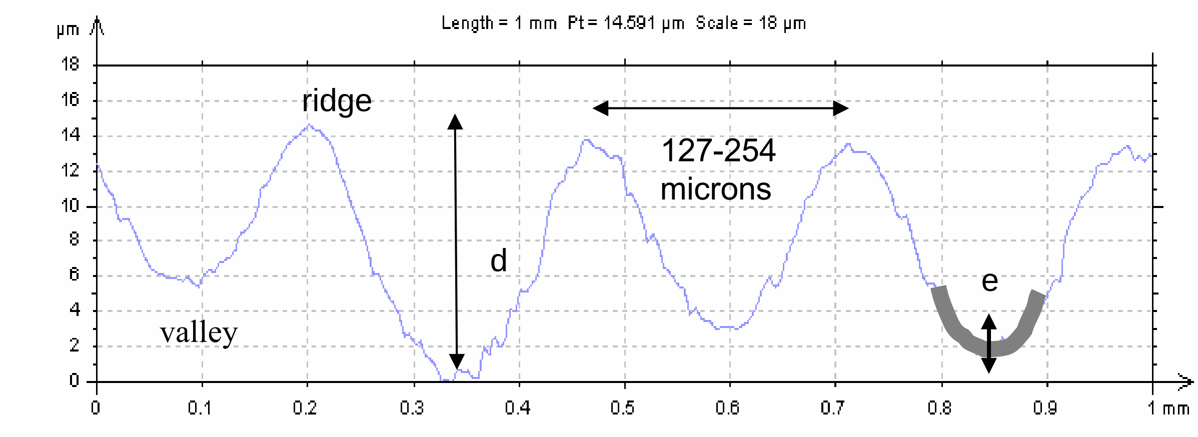
History

- 1859 Leon Scott invents *Phonoautograph* paper recorder
- 1877 Thomas Edison invents sound reproduction on vertically embossed tin foil cylinder, *Phonograph*
- 1885 A.G.Bell and Tainter introduce wax cylinder
- 1887 Emile Berliner invents disc *Gramophone*, lateral groove
- 1925 Western Electric *Orthophonic* (electrical) system, ends 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*), ends the “**Analog Era**”
- 2001 Apple *IPOD*

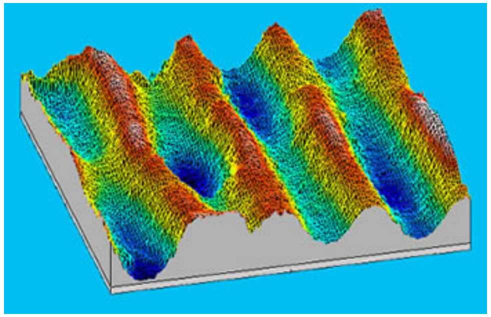


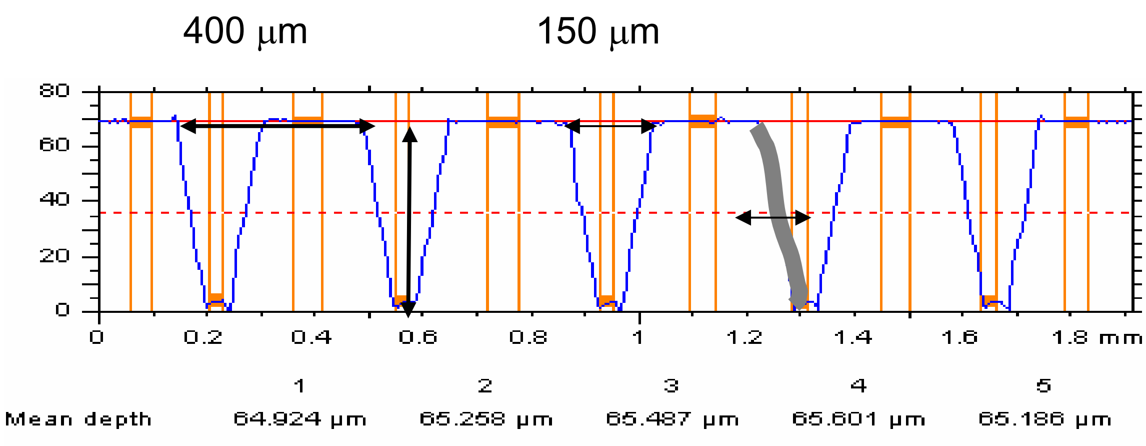


Discos fonográficos Pathé
Caras y Caretas (7/7/1906)



Cylinder surface





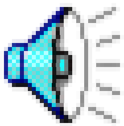
Disc surface

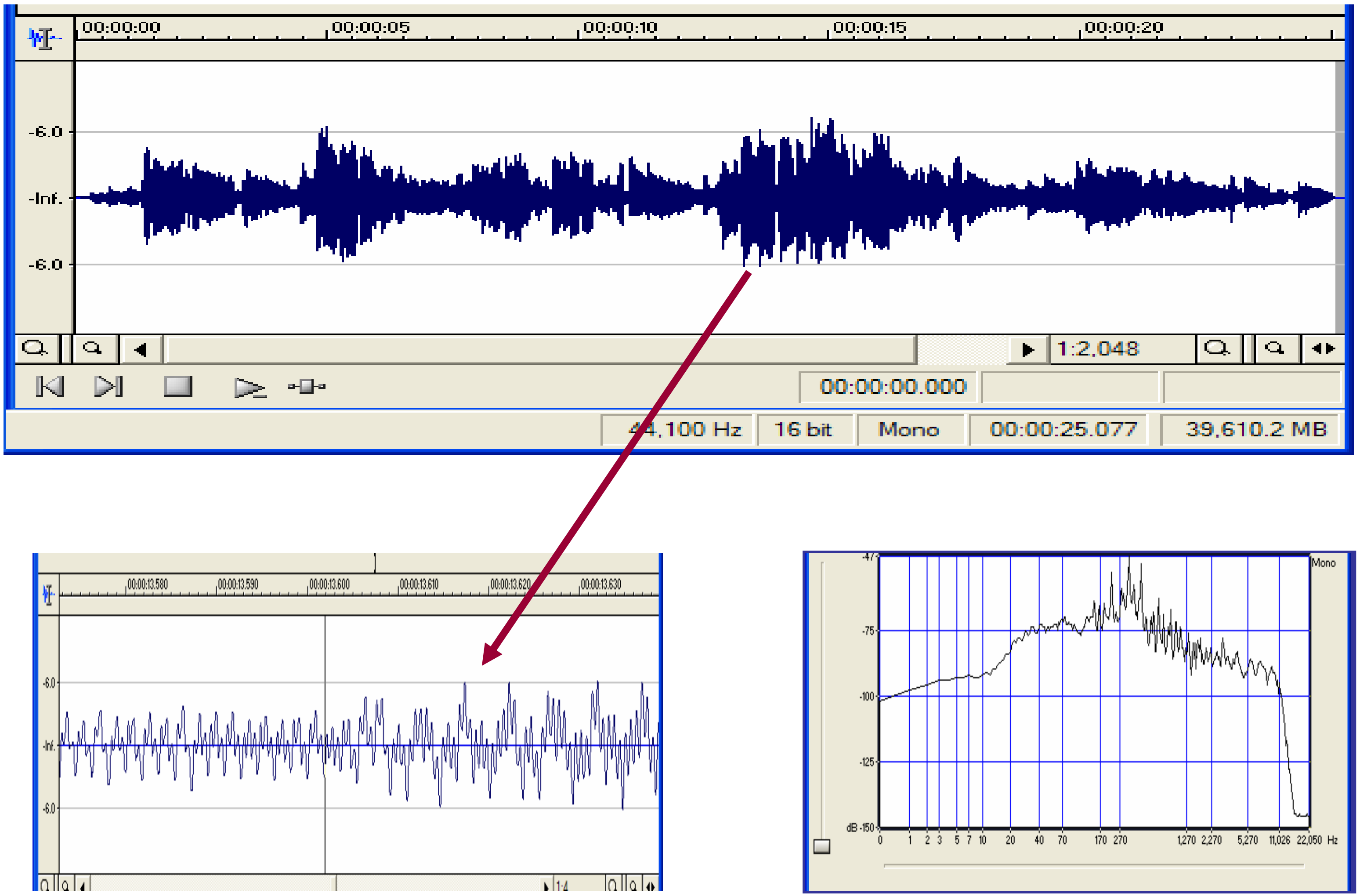
Debate during acoustic years between cylinder (constant surface speed) and disc (ease of manufacturing and storage) technologies.

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

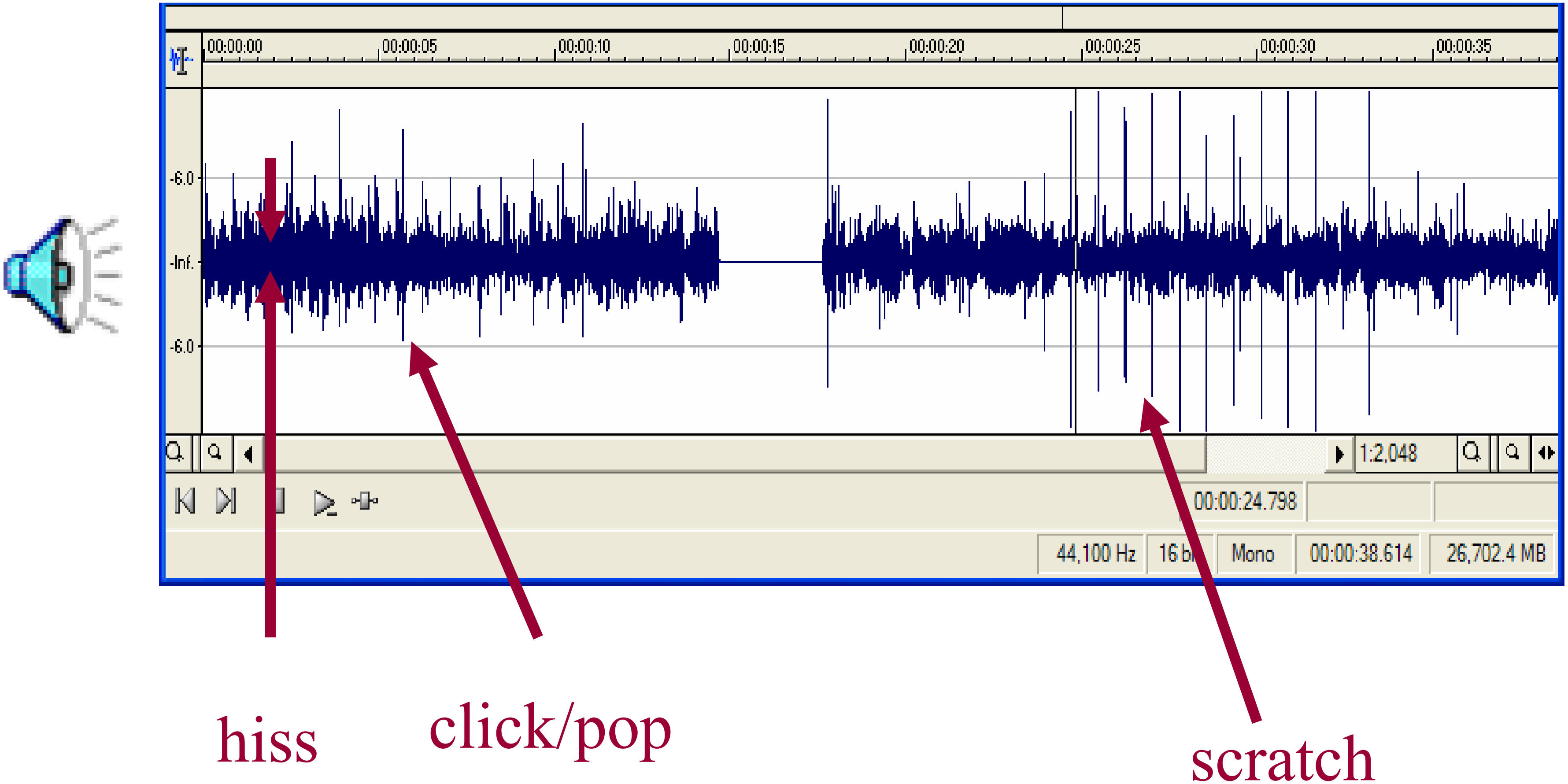
Need to measure sub-micron features over entire surface of record

Sound




00:00:00
00:00:05
00:00:10
00:00:15
00:00:20
-6.0
-Inf.
-6.0
1:2,048
00:00:00.000
44,100 Hz
16 bit
Mono
00:00:25.077
39,610.2 MB
00:00:13.580
00:00:13.590
00:00:13.600
00:00:13.610
00:00:13.620
00:00:13.630
Mono
-75
-100
-125
dB -150
Hz

Sound + Noise



00:00:00
00:00:05
00:00:10
00:00:15
00:00:20
00:00:25
00:00:30
00:00:35
-6.0
-Inf.
-6.0
1:2,048
00:00:24.798
44,100 Hz
16 bi
Mono
00:00:38.614
26,702.4 MB
hiss
click/pop
scratch

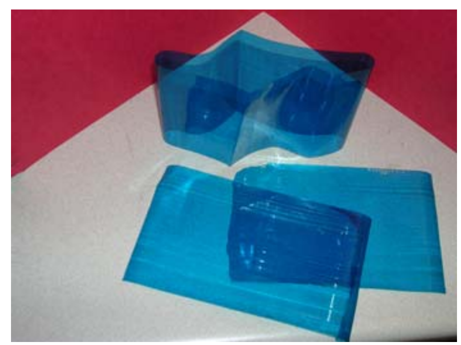
Diverse media

Shellac disc ("78"): main commercial media before vinyl (1950's), scratches, wear, breakage

Wax and plastic cylinders: mold growth, wear, breakage

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

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



Metal stampers

Modern Audio Restoration

- Materials (labor intensive)
  - Cleaning
  - Stylus
  - Repair
- Signals
  - Analog and digital filters, hiss, clicks, pitch
  - Many commercial s/w products
  - Multiple samples, alternate sides of the groove…
- All aspects require contact to media and skill

Non-Contact Digital Imaging

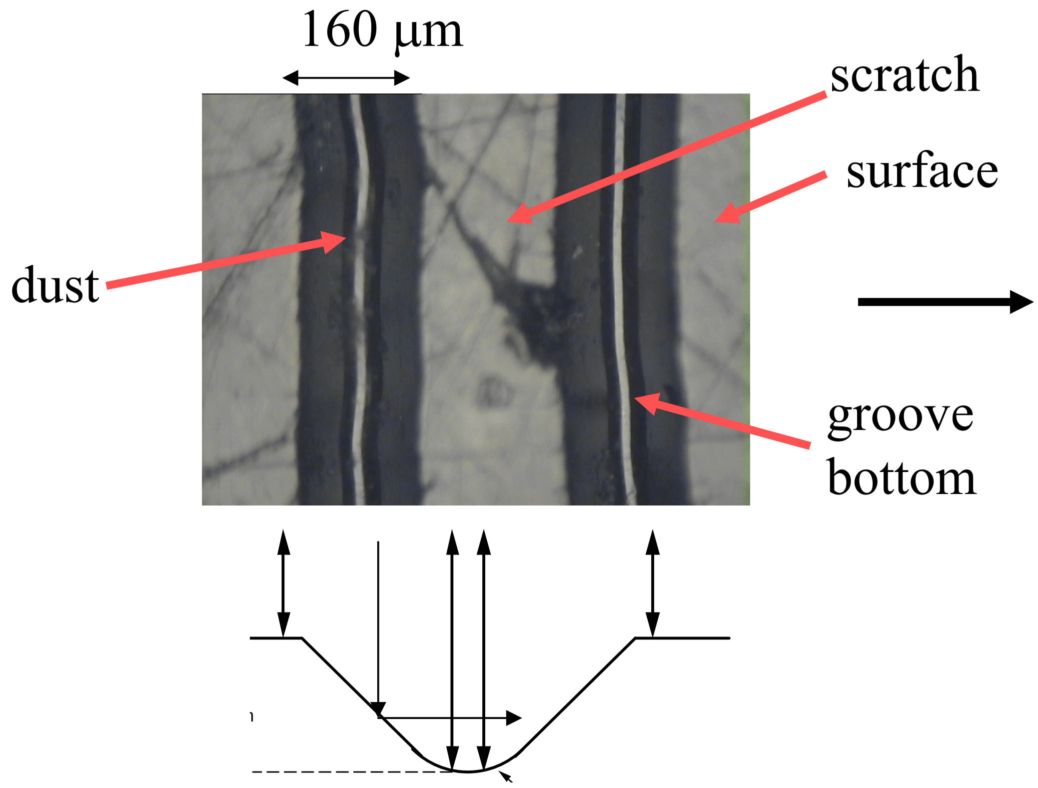
- Protects samples from further damage
- Repair existing damage through "touch-up"
- Offload many aspects of restoration to automated software

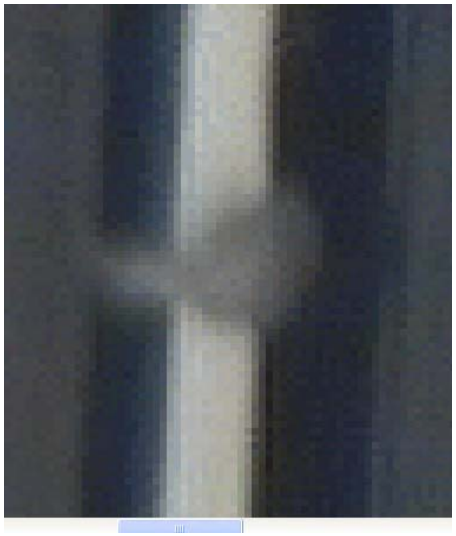
A "smart" copying machine for records

The Method

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

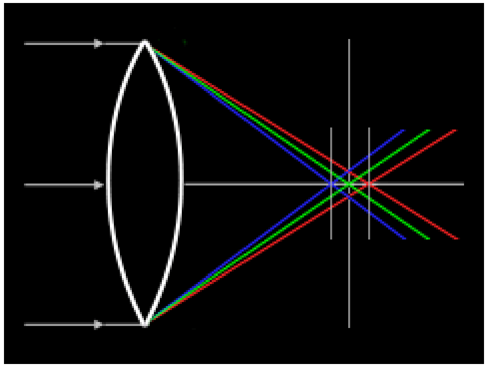
2D Imaging: Electronic Camera

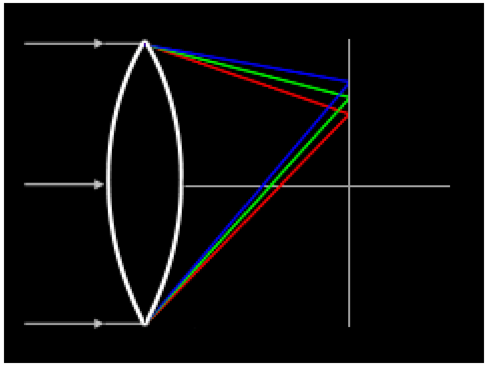




- Suitable for disc with lateral groove
- Require 1 pixel = ~ 1 micron on the disc surface

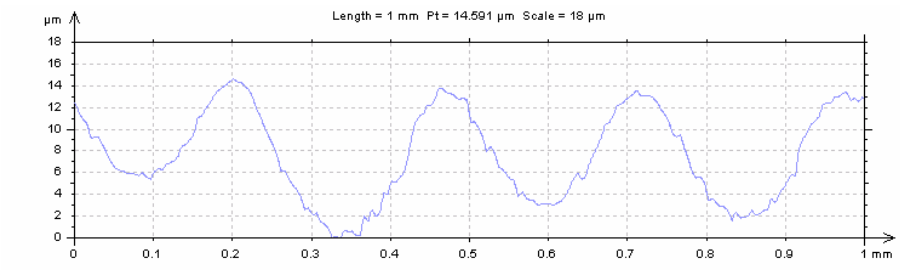
Chromatic Aberration

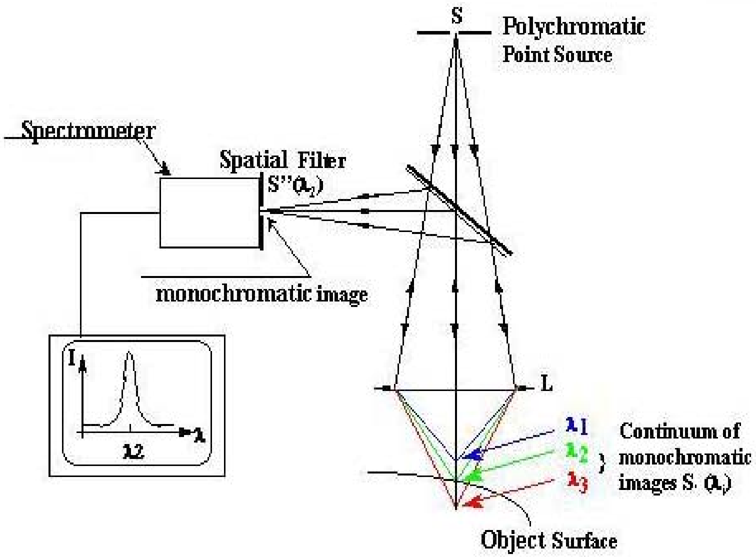


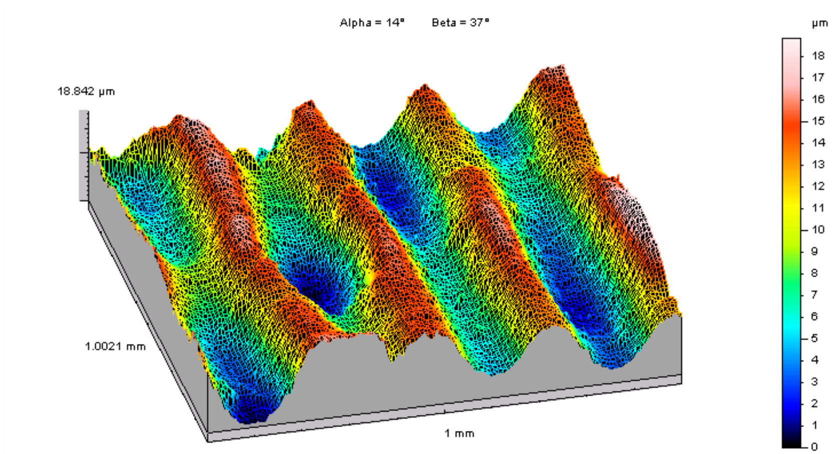


3D Imaging: Confocal Scanning Probe

Required for cylinder with vertical groove modulation.







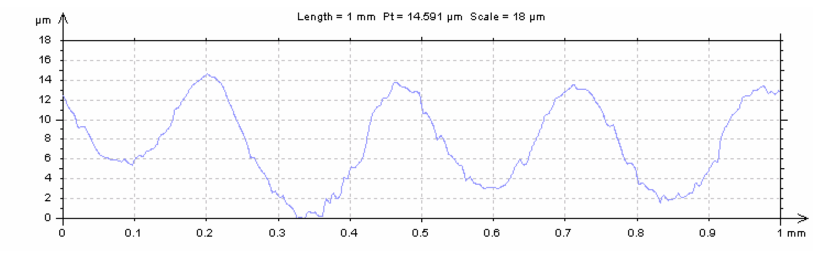
Up to 4000 pts/second

Surface of an Edison cylinder

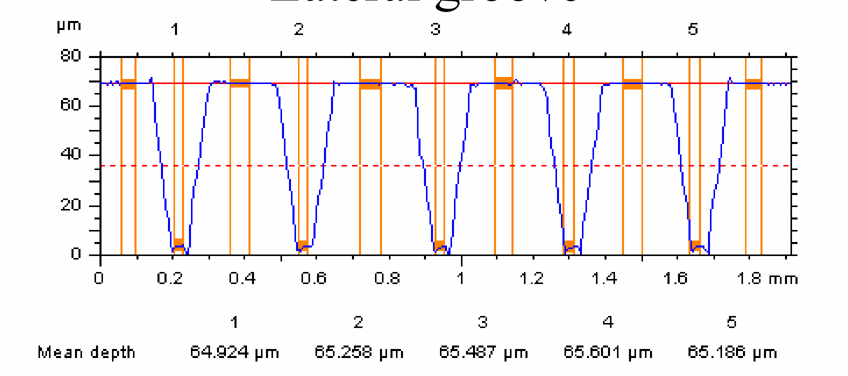
Speed and Data

- 2D scans for lateral discs
  - Fast camera: ~10 min for 78 rpm disc
  - 50 Mb / 1 s of raw images
  - 1.5 Mb / 1s processed
  - 88 Kb / 1s audio (44/16)
- 3D scans for vertical cylinders
  - Depends upon grid, probe rate
  - 12 KHz sampling: 3-10 hours
  - 96 KHz sampling: 24-80 hours
  - Factors of 2-4 may be available soon
- 3D for deep groove lateral discs
  - Much slower probe rates are probably required

Vertical groove



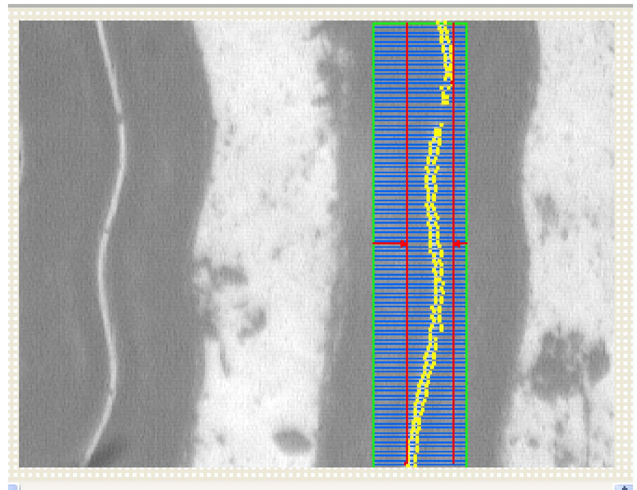
Lateral groove



Key 3D issues are slope and depth

Image Processing

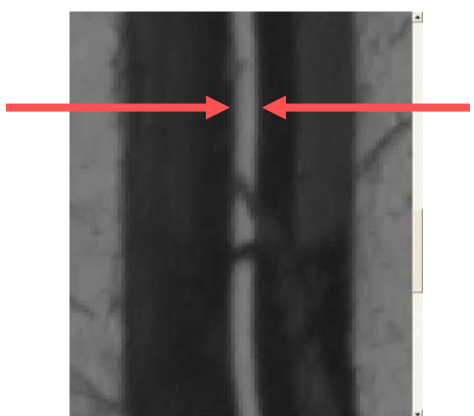
Intensity

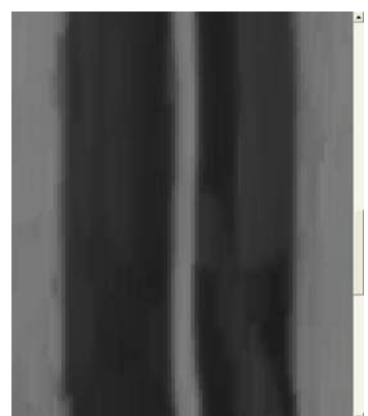


Edge finding

Knowledge of groove geometry provides a powerful constraint for rejecting debris and damage

Groove Geometry constraint

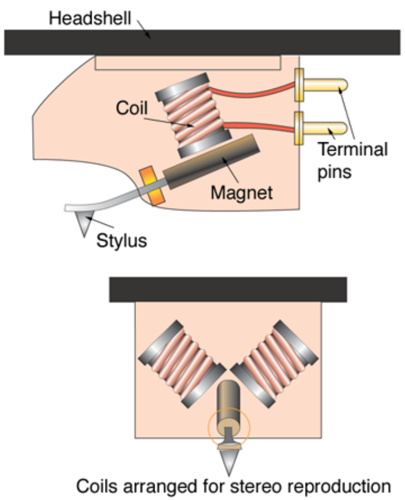


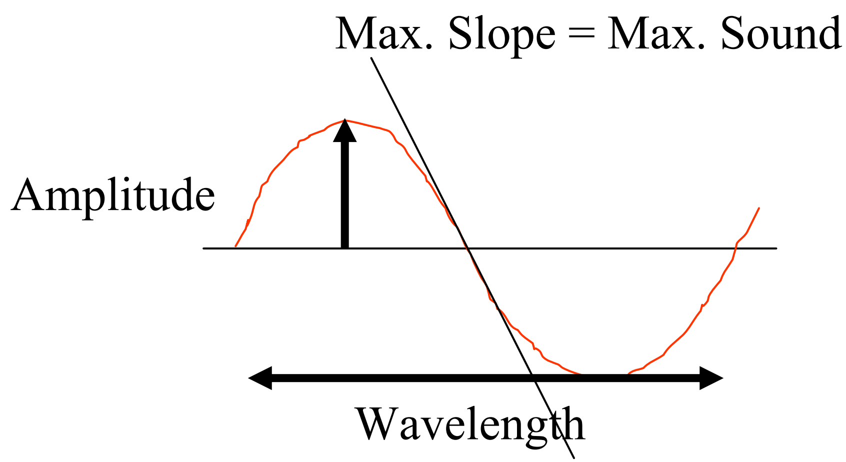


dilation

What is the relationship between “groove” and sound?

Electro-magnetic case



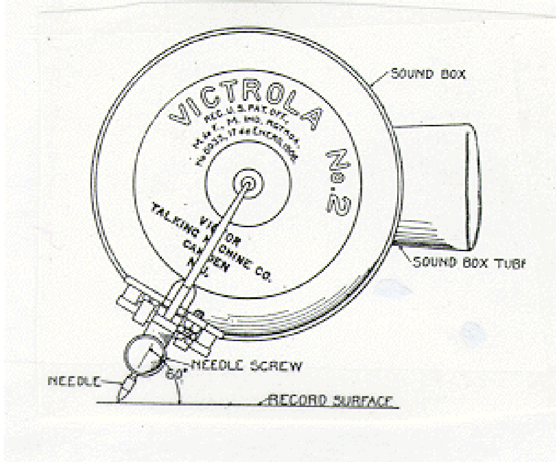


Sound = Stylus Velocity

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

(“constant velocity condition”)

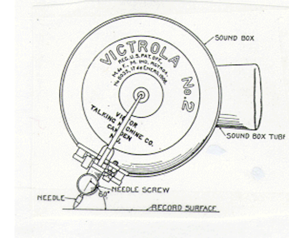
Acoustic case



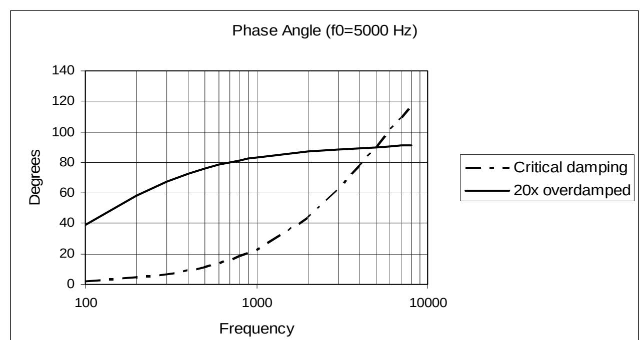
Horn

Diaphragm + Stylus

Acoustic Case



- Horn extends response (of small diaphragm) to lower frequencies
- Plane waves: pressure and velocity are proportional and in-phase
- Horn supports plane waves: true above a cut-off frequency for sufficiently large horn, depends also upon profile
- Diaphragm is a driven harmonic oscillator
- Want "flat" frequency response: requires overdamping
- Diaphragm velocity follows driving force (fails at high frequency where mass dominates (~5KHz))
- "Constant velocity" condition applies *approximately* but no deliberate equalization is possible.
- Response
  - Typical ~1 decade
  - best case 100 Hz-5KHz



Comparison

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

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

Summary of Method

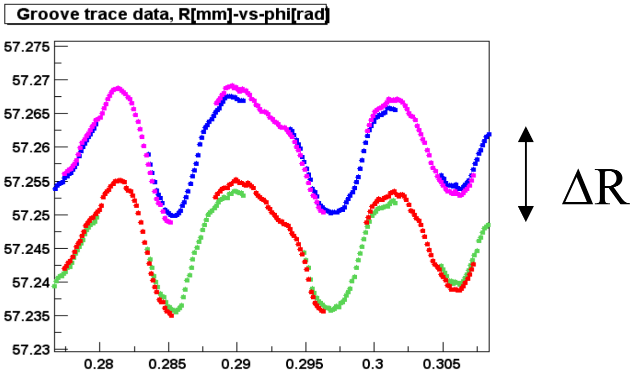
- 2D approach only for laterally modulated grooves
  - Requires good feature
  - Imaging is fast
  - OK for access copies?, but preservation?
- 3D approach required for vertically modulated groove
  - Extract maximum information
  - Imaging is slow
  - Ultimate approach for preservation needs

Test of Concept

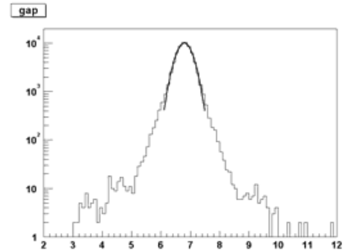
- 2D: Study of 78 rpm shellac discs ~1950
- Use commercial machine (from ATLAS project) – very slow…
- Video zoom microscope, auto focus, precision table motion
- Programmable motion, image analysis & reporting
- Wrote program to measure groove

Chronicle / Darryl Bush

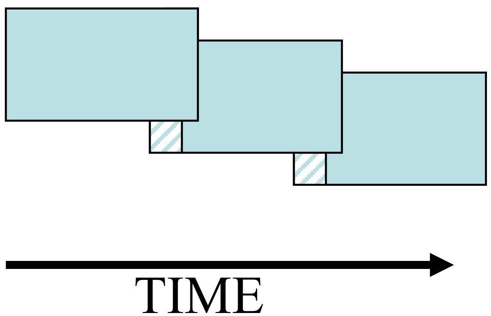
Chronicle / Darryl Bush



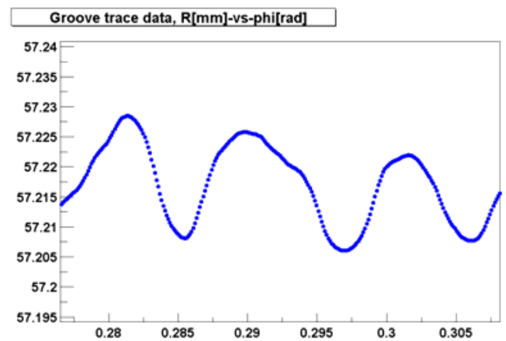
ΔR distribution



Width across groove bottom

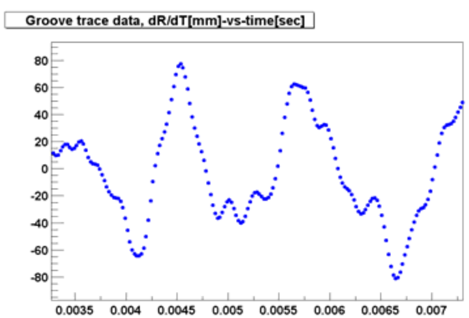


Measurement spacing along time axis ~ 66 KHz



Align
Average
Filter with ΔR<cut

Measure slope at each point (stylus velocity)



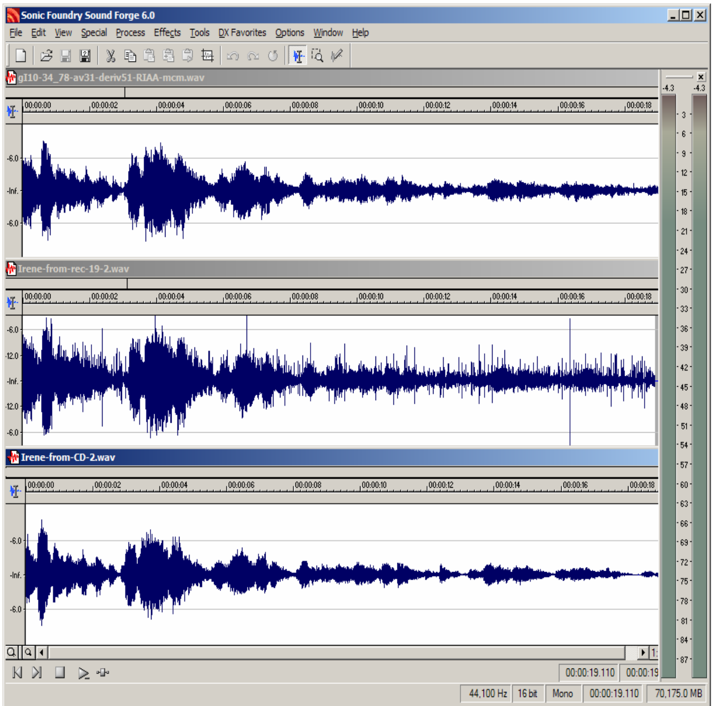
Waveform comparison

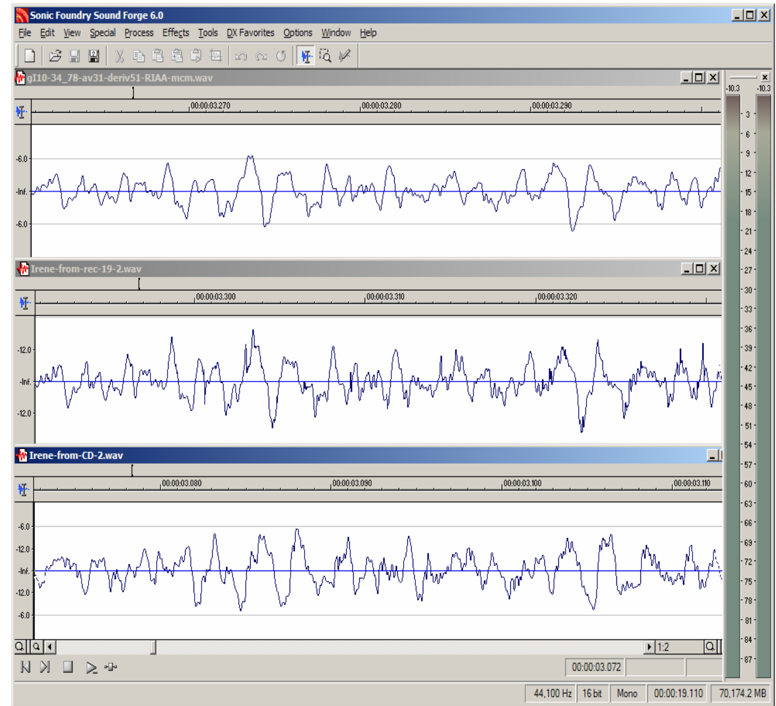
19.1 seconds | 0.04 seconds

optical

stylus

CD



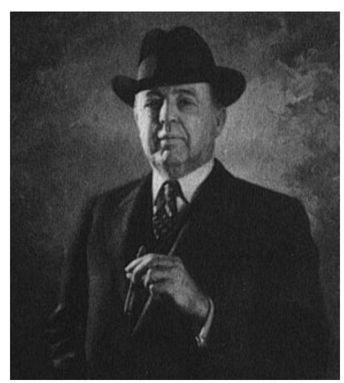


- Clear reduction in “clicks and pops”
- Similarity of fine waveform structure

Sound Comparison

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

- Sound from the CD of ***re-mastered tape***.
- Sound from the ***mechanical (stylus)*** readout.
- Sound from the ***optical*** readout.
- optical + commercial noise reduction

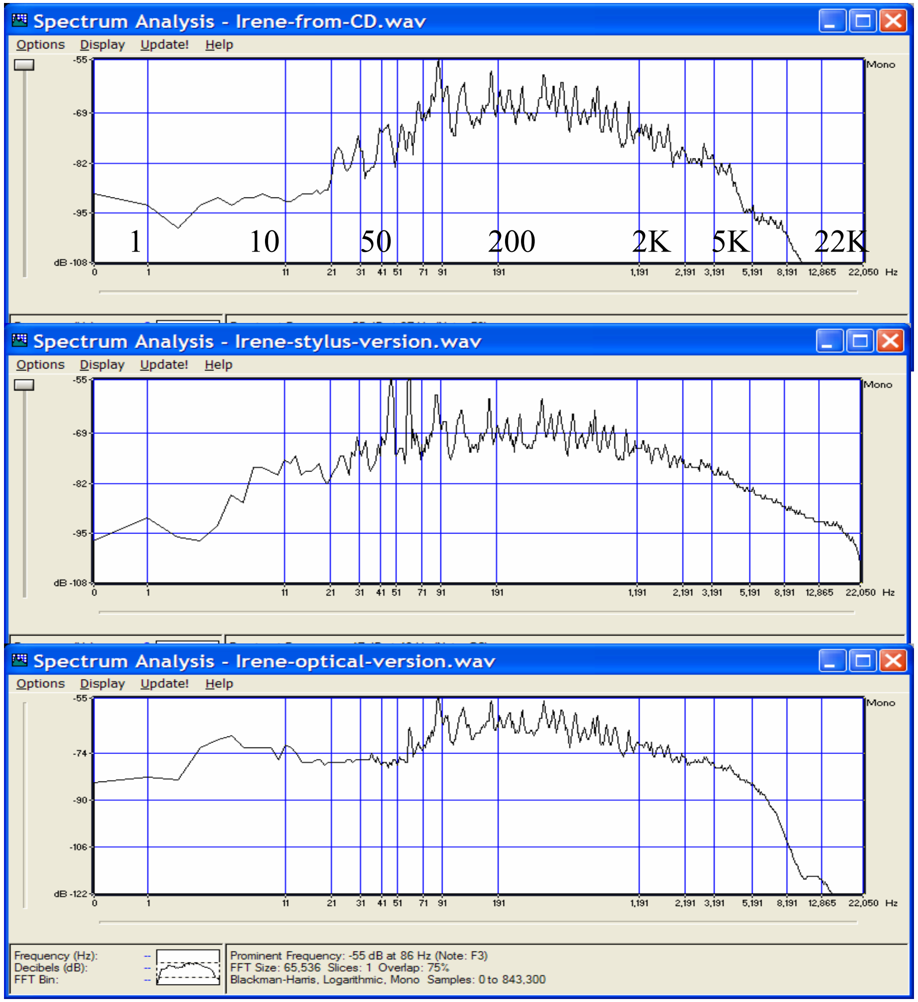


Frequency

CD version

Stylus version

Optical version

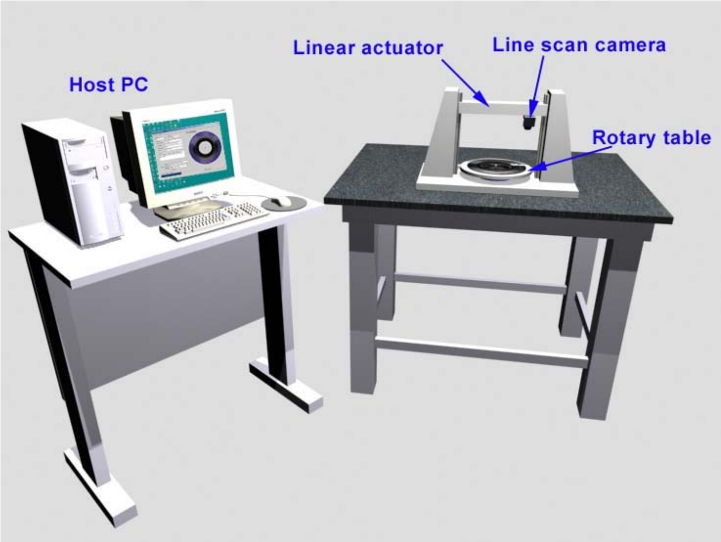


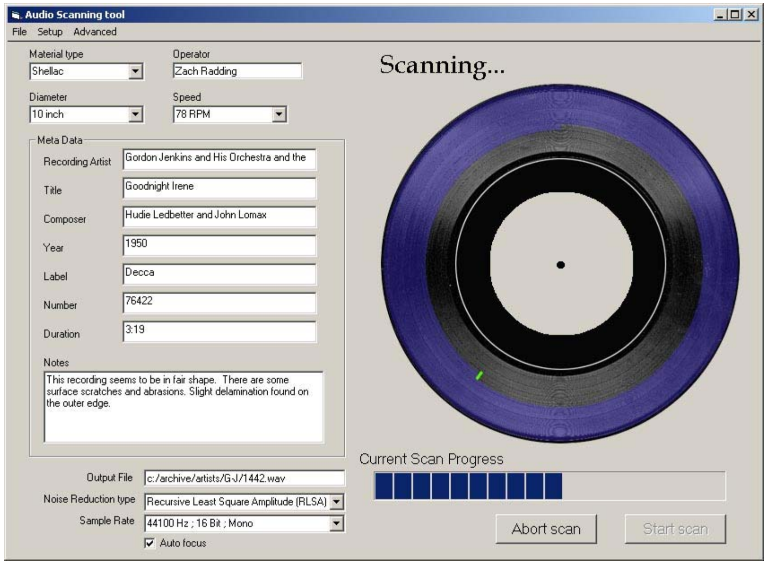
Library of Congress: Directions

1. The 2D test was promising, can you make a machine to run near real-time on discs? Could it address mass digitization needs? What about sound quality?
   - IRENE proposal (approved by NEH 1/05)
2. A research program to further the 3D technology.
   - Underway with support from LC, Mellon

I.R.E.N.E.

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



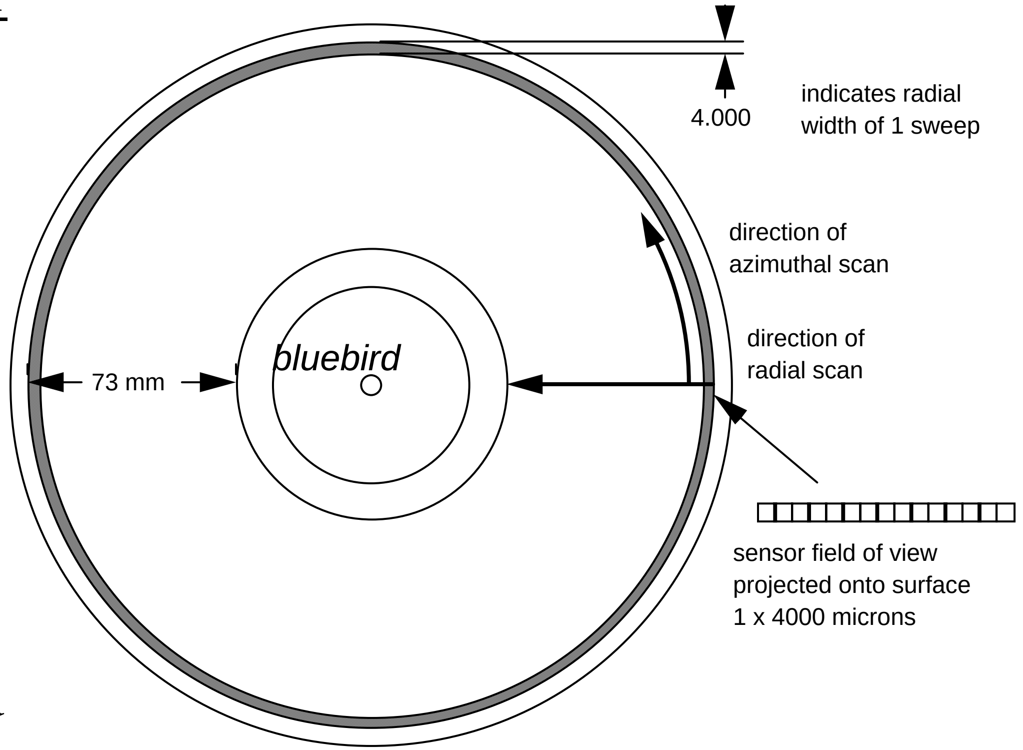


- ~1 year development and construction
- Projected scan time 5-15 minutes
- Provide statistical measures of media condition
- Production-like machine and test-bed for future development

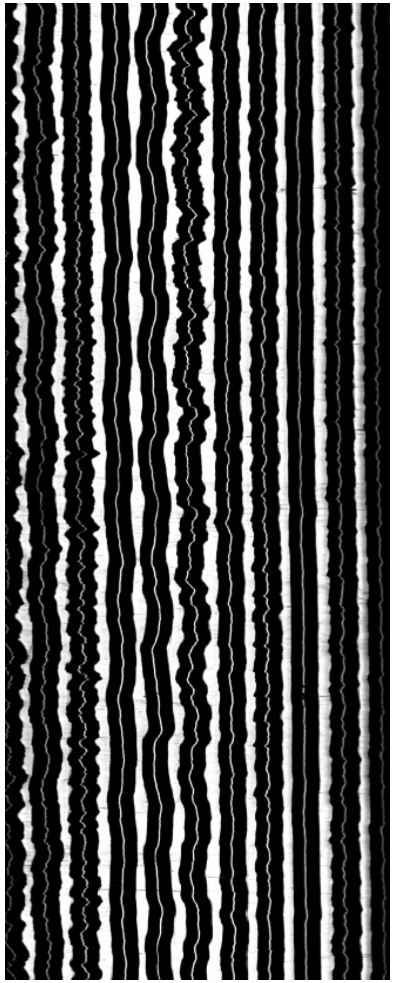
Basic Features and Goals

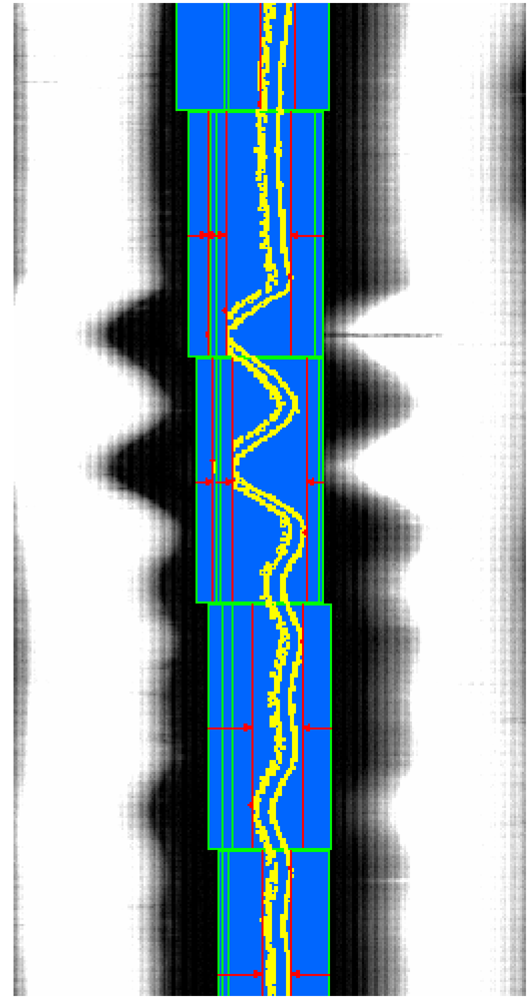
- 2D approach: image groove bottom and/or top.
- Emphasize throughput.
- Encompass as much variation in media as possible.
- Handle broken discs.
- Facility to (temporarily) flatten flexible media
- Off-the-shelf components, friendly interface.
- Provide a test bed for the mass digitization application.
- LC perform test on sample collection 2006

- 4000 pixel, line scan sensor @18 K lines/s
- Magnify to 1 pixel = 1 µm
- 7.6×10^5 lines/outer ring
  - **390 KHz sampling**
- Time/ring = 40 seconds
- 73 mm / 4 mm = 19 rings
- 19 x 40 sec = 13 minutes
- Reduce with variable speed on inner rings: 9 minutes
- Scan time decreases linearly with sampling!!!.



Based upon 10 inch, 78 rpm geometry





IRENE Test Platform

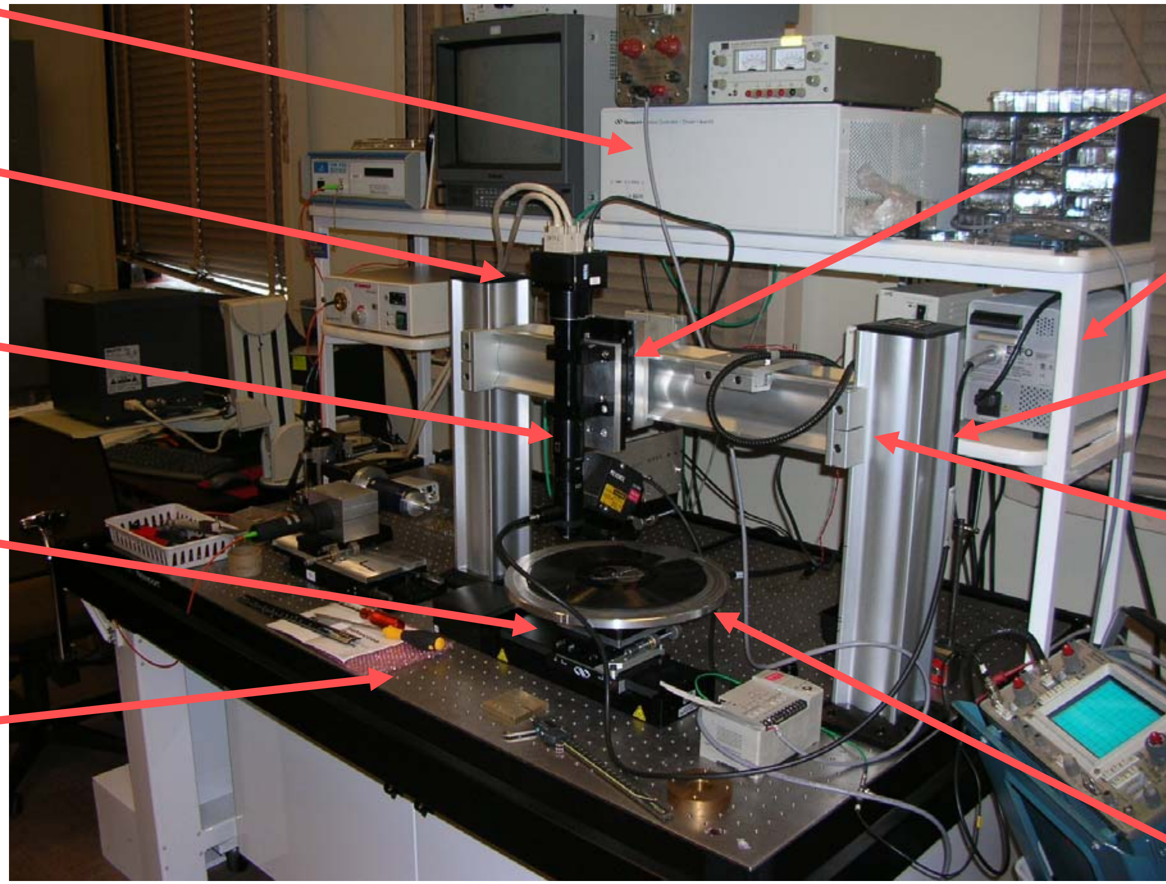
Stage motion controller

Line scan camera

Main lens

Motion stages

Vibration isolation table



Vertical stage for focus

Light sources

Fiber bundle

Support arch

Focus height sensor

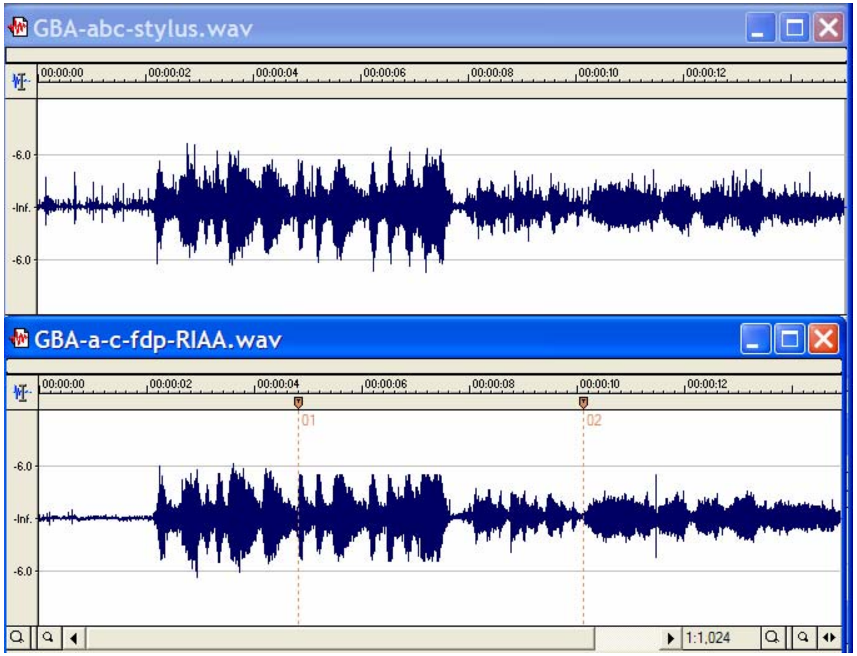
Turntable and disc

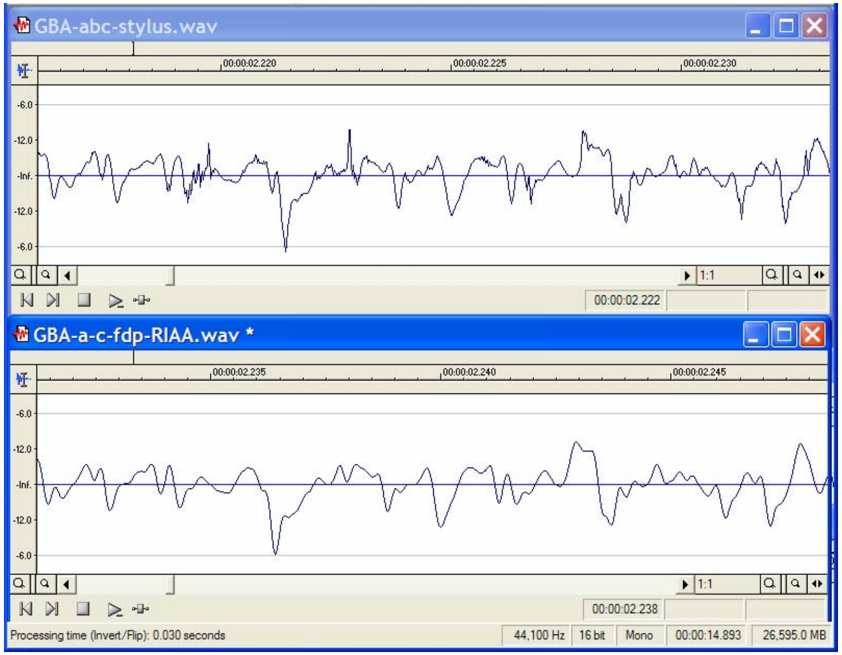
Tests of IRENE Design

- Preliminary results from prototype configuration
  - Low intensity illumination (13 s scan / 1 s audio)
  - 100 KHz time sampling
- Shellac 78 rpm discs
  1. Good condition
  2. Very worn disc
  3. Distorted audio
- Acetates
  - 1950's studio music take
  - 1938 spoken word

Good Shellac: Waveform Comparison

Stylus





IRENE test platform

Sound Comparison

God Bless America

Composed by Irving Berlin, performed by Kate Smith, Victor release

- Stylus version
- Optical version using IRENE test platform

Test: Defects etc.

Dirty and worn

When You and I Were Young, Maggie

Composer: Johnson and Butterfield

Performed by Charles Harrison

Victor 17474-B

Stylus version

IRENE test scan

Some audio distortion

Uchar Kupietz (folksong)

Performed by Vera Smirnova

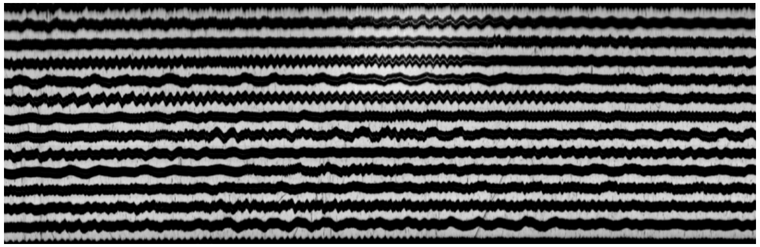
Columbia 20115-F

Stylus version

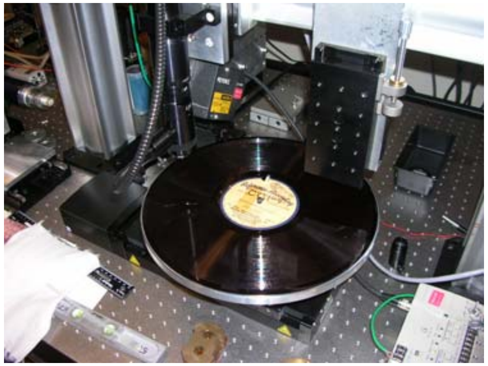
IRENE test scan

Acetates

45 rpm fine groove with
No groove bottom image
Labeled: "Jailhouse Rock,
RCA property"

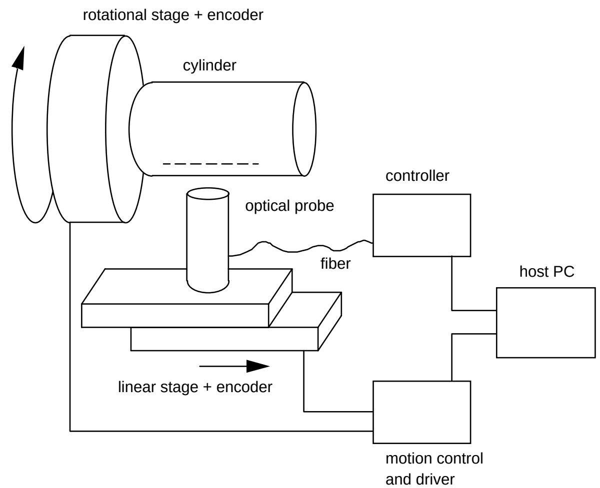


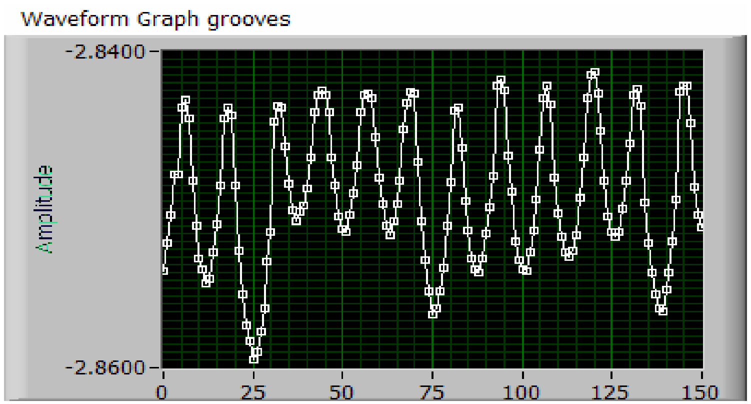
78 rpm lacquer on glass
Label: Howard Hughes,
Collier Award 1939

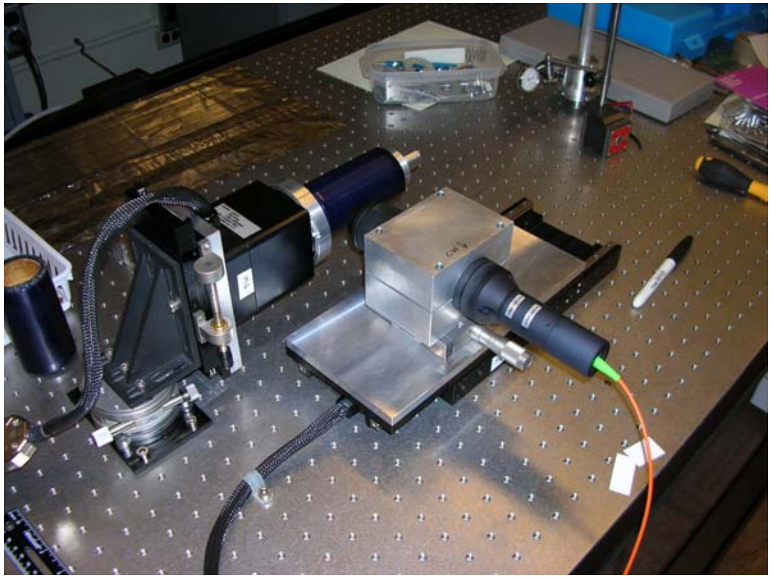


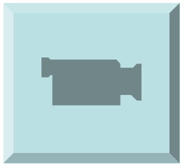
3D Study of an Edison Cylinder

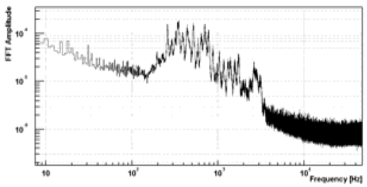
Utilize confocal scanning probe at 300, 1000, 4000 Hz,
7.5 μm spot, 10 μm points
Angular increment = 0.08 - 0.01° = 12 - 96 KHz time sampling



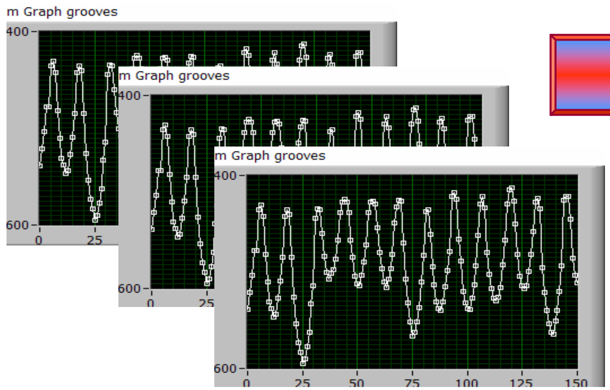




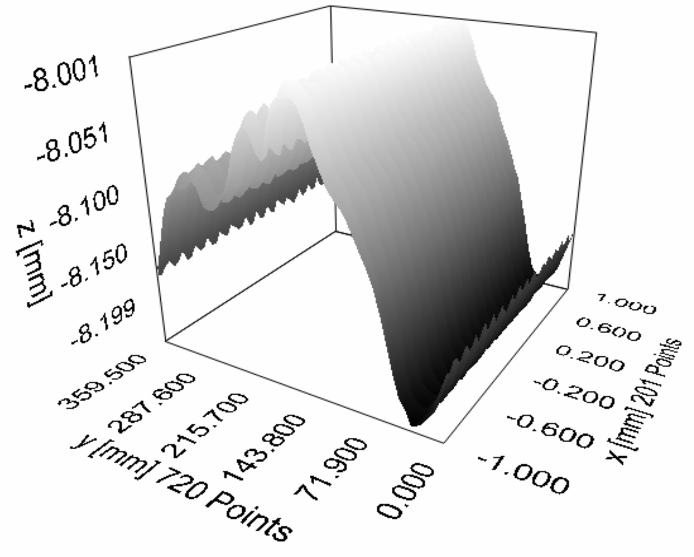




Sample at 96KHz to minimize effect of aliasing



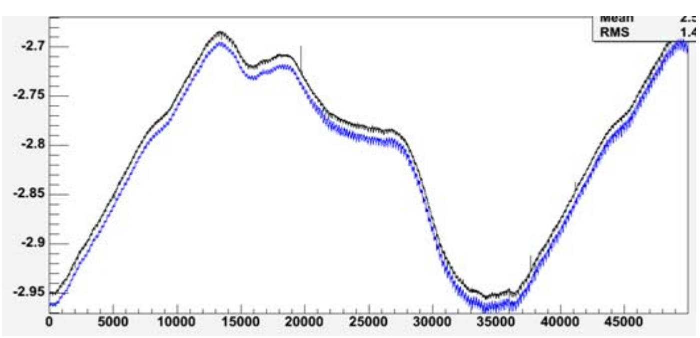
Sequential axial scans



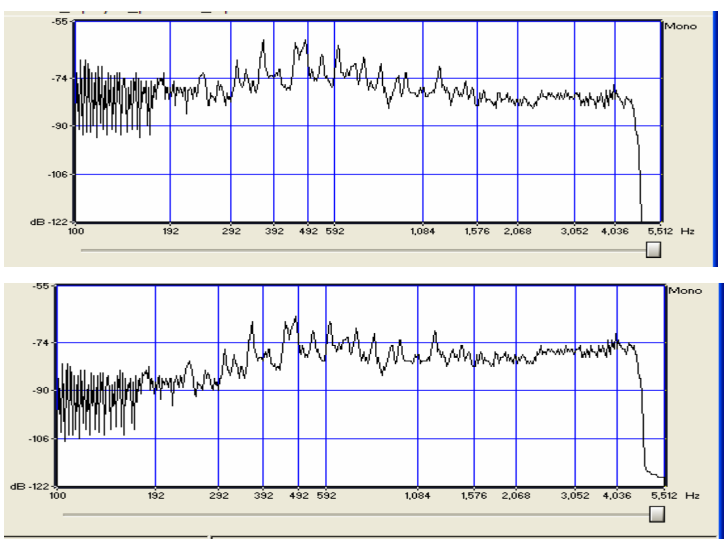
Subtract valleys from ridges to correct for overall shape

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

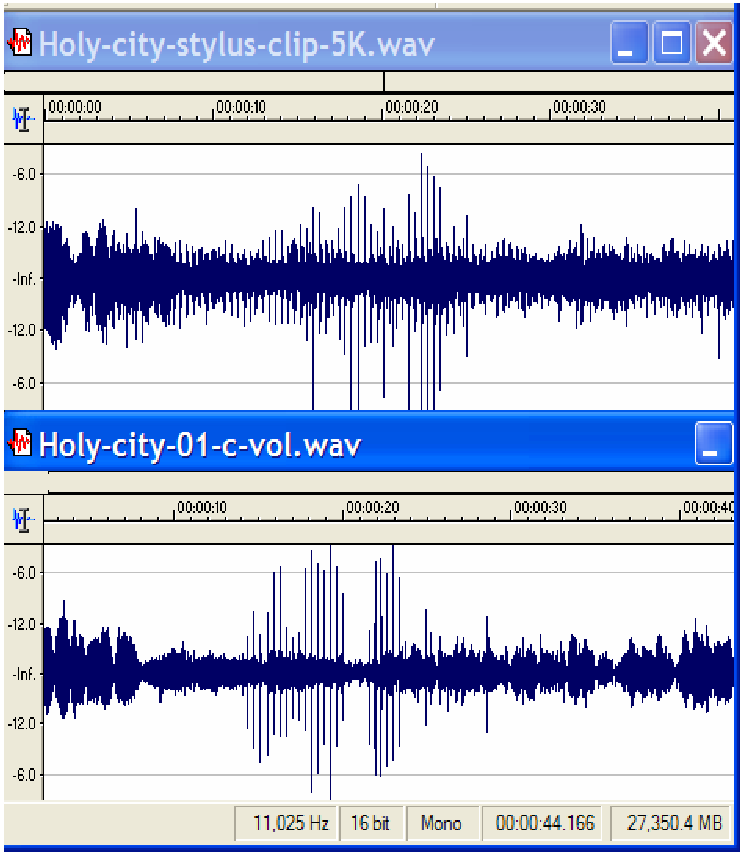
(Ridges provide (approx), geometrical reference)

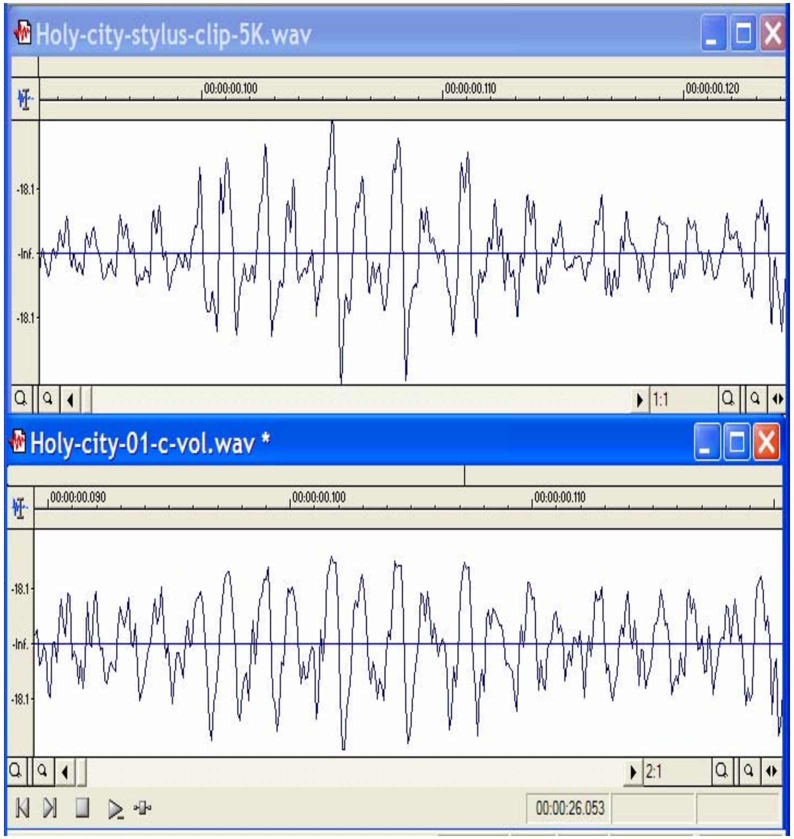


d/dt



Waveforms


Holy-city-stylus-clip-5K.wav
Holy-city-01-c-vol.wav
11,025 Hz
16 bit
Mono
00:00:44.166
27,350.4 MB

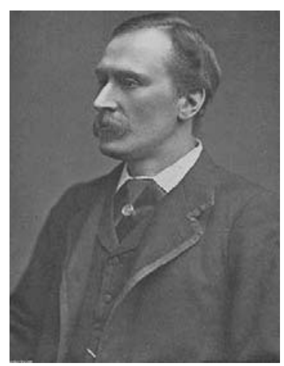

Holy-city-stylus-clip-5K.wav
Holy-city-01-c-vol.wav *
00:00:26.053

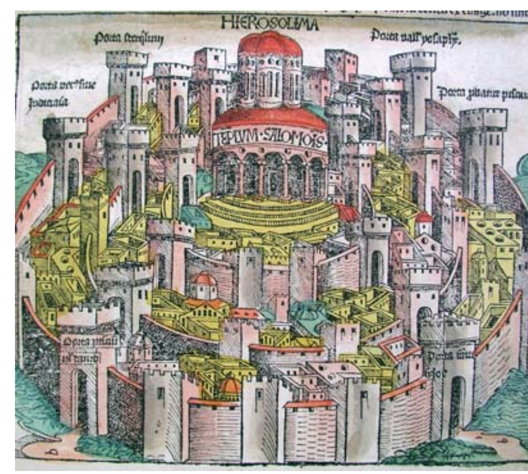
Sound Comparison

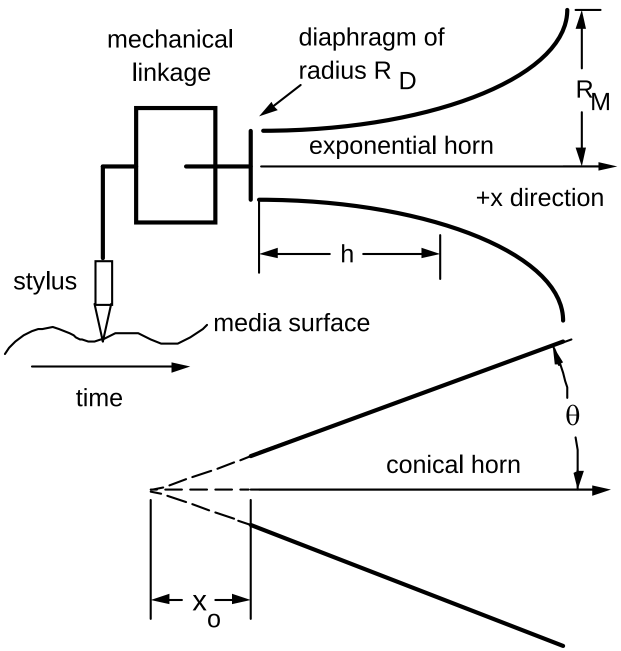
- The Holy City, composed by Stephen Adams,

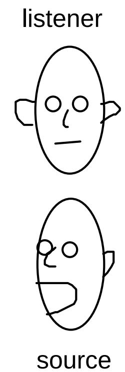
The Edison and Skedden Mixed Quartet, Amberol 1601

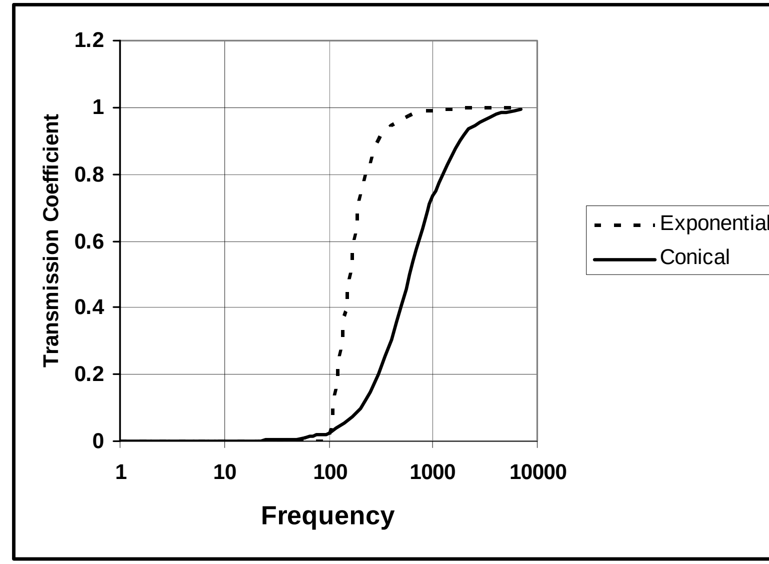
- Stylus version - flat
- Optical version (1 KHz probe rate) - flat
- Optical version + commercial filter + EQ











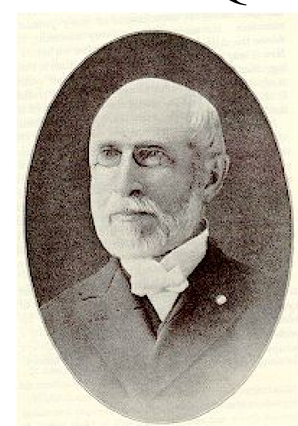
Response of horn and diaphragm at low frequency can modify response and deviations from “constant velocity” characteristic.

2nd Sound Comparison

- “Just Before the Battle, Mother”, composed by George F. Root, performed by Will Oakland and Chorus 1909,

  1516 (..76; 4M-297-2) originally as Amberol #297 1909

- with stylus, flat equalization
- Optical version, flat equalization
- + commercial noise reduction + low frequency boost EQ



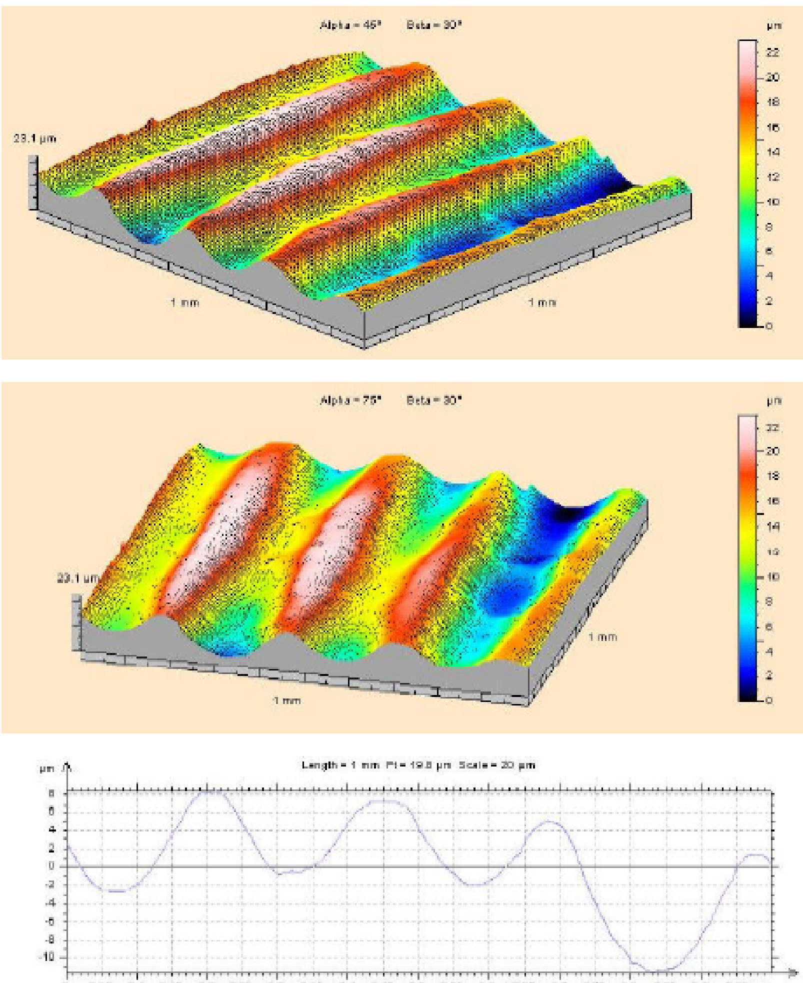
3D Research

- Study data quality versus probe speed and grid spacing to optimize overall scan time.
- Study media with mould growth and other damage..
- 3D studies of other media.

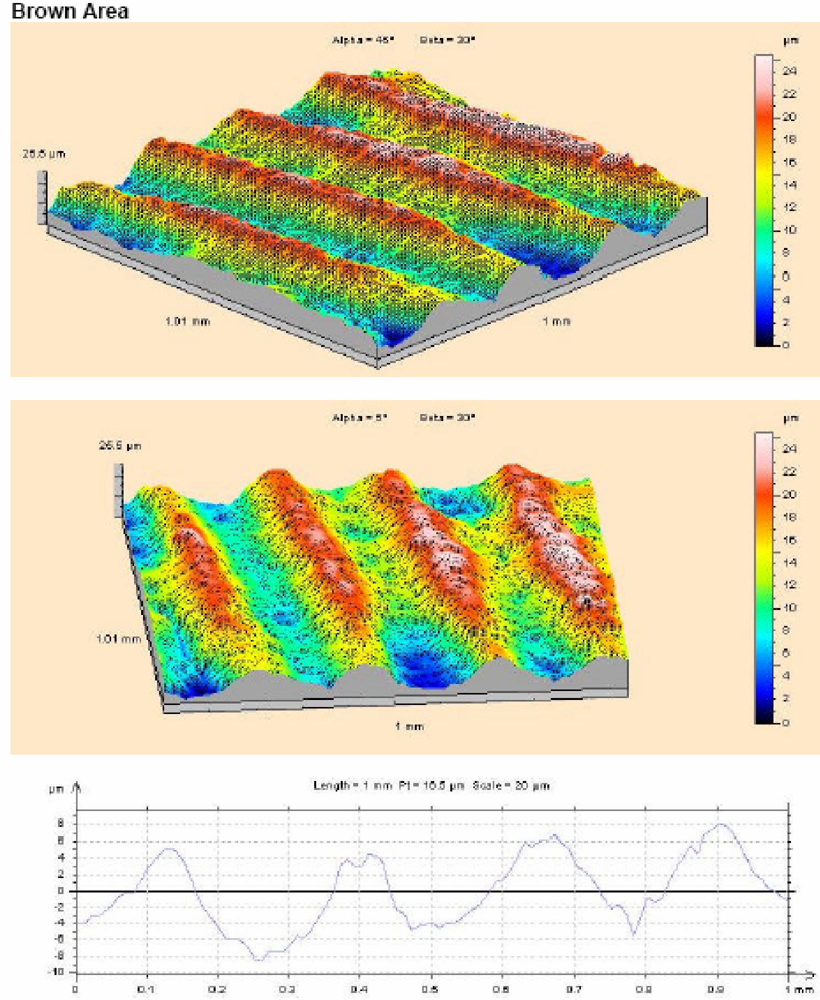
Scan Time Issues

- Factors which effect scan time
  - Probe measurements / second
    - Now at 4K /s
    - Tests have been done at 10K and 30K
    - Key issue is bright light source
  - Time sampling
    - Tests done at 96 KHz, 24 KHz, 12 KHz
  - Points across groove
    - 10 is sufficient for typical cases - how few?
- Present case
  - 4K probe + 96 KHz sample + 10 pts/groove ~ 30 hrs
- What is ultimate ("access") case?
  - 30K probe + 12 KHz sample + 5 pts/groove ~ 30 min

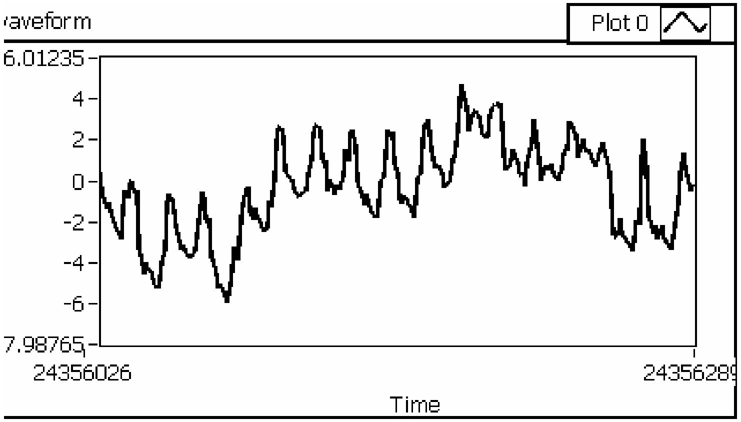
Clean Area

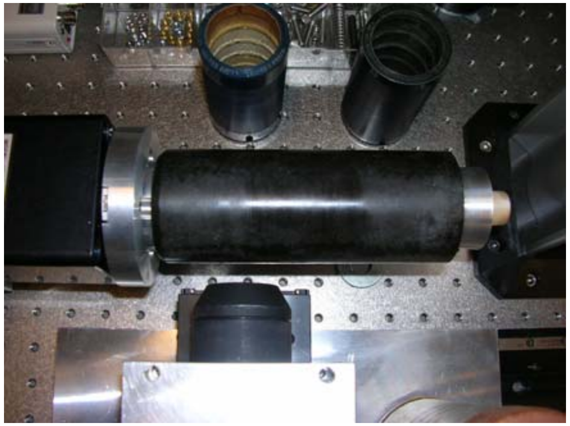


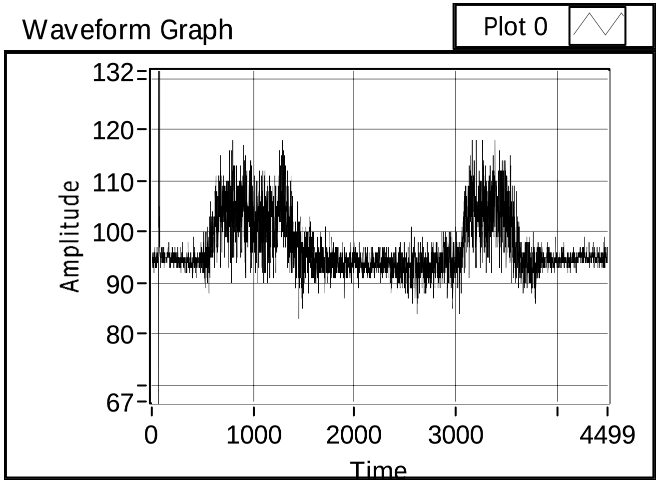
Brown Area

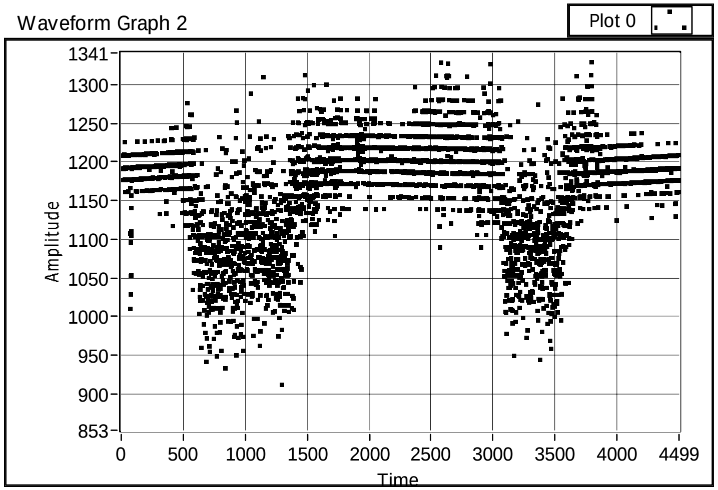


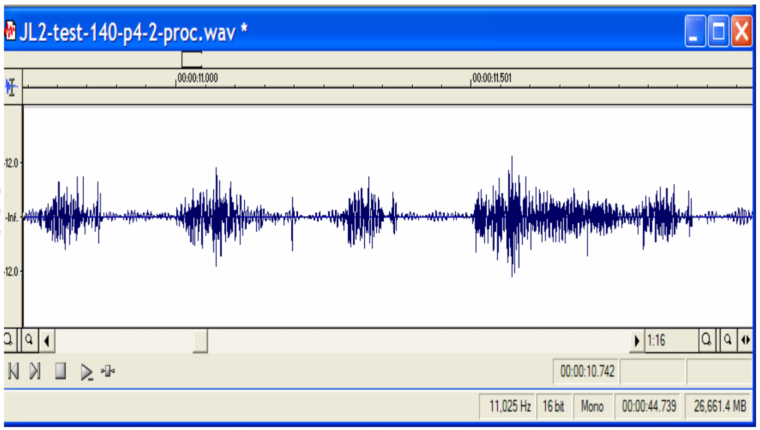
Cylinder with mold











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

From Top Quarks to the Blues
Particle Tracks Tune Up Music
Physicists Seek to Digitize Music, Restore Media
Using high-energy physics to preserve old records
Scientists find new way to play old records
Optical Metrology Reconstructs Audio Recordings
From the Higgs Boson Particle to Leadbelly
Teilchenphysik im Dienste des Kulturerbes
Teilchenphysiker retten das musikalische Erbe der Menschheit
Particle Physics Recovers Music From the Past
New technique preserves old sounds
Digitizing groovy records
De la Física a la Fonografía
Physiker retten Schellack-Aufnahmen
Particle physicists to help restore old audio recordings
How to listen to old records in the 21st century
Particle physicists rescue rare vinyl recordings
Φυσικοί βρίσκουν τρόπο να βελτιώσουν τον ήχο
Der Bosonen-Blues - Teilchenphysiker helfen alte Tonaufnahmen von Schellackplatten und Wachszylindern zu retten
Physicists find method to improve audio
Laser pour vieux vinyles
LISTENING TO RECORDS BY LOOKING AT THEM
Aus alt mach neu
Fizycy ratują stare winyle
Playing Old Records (No Needle Required)
New Hope For Old Sounds
Optical Metrology Reconstructs Audio Recordings
Digitizing the voices of the past
Science perfects sound of century-old recordings
Virtual Record Player Preserves Historic Recordings
Particle Tracking Tunes Up Music
Physicists Seek to Digitize Music, Restore Media
Groovy Pictures: Extracting sound from images of old audio recordings
How to listen to old records in the 21st century
Rescuing Recordings
REAL LIFE NEWS: PRESERVING ANCIENT RECORDINGS
Técnica permite recuperar LPs danificados pelo tempo
Inspirado na física de partículas, método digitaliza gravações sem riscos e chiados

Why I read Physics Today

Conclusions

- Image based methods have sufficient resolution to reconstruct audio data from mechanical media and reduce impulse noise.
- 2D approach may be suitable for mass digitization. IRENE will address this and other key issues.
- At present 3D methods are suitable for reconstruction of particular samples since they require ~hours per scan.
- Ongoing 3D research program addressing issues of ultimate scan time, damaged media. A 3D "IRENE" system next?
- Considerable professional and public interest
- Info at URL www-cdf.lbl.gov/~av

V.Fadeyev & 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).