New Technologies for Preservation and Access to Recorded Sound History

Sound was first recorded in the 1850's by the French inventor Leon Scott de Martinville who devised a mechanism to represent sound waves on paper. His "phonautograph" was a mechanical precursor to the modern storage oscilloscope but originally featured no possibility for reproduction. Sound was first recorded and reproduced by Thomas Edison in 1877. Edison mechanically captured sound waves and embossed the resulting vibrations on a tin foil cylinder. From that time, until about 1950 when magnetic tape came into broad use, mechanical media such as foil, wax, plastic, shellac, and lacquer were the predominate materials which held recorded sound. Today, vast collections of historical sound recordings reside in the major archives such as the Library of Congress and the British Library, and in numerous other collections at museums, libraries, and academic institutions worldwide. The recordings contained within these collections are broad, diverse, and of great historical significance. Among the categories held in these collections are the following.

- Field recordings of linguistic, cultural, and anthropological materials
- Primary recordings of key musical artists, poets, and writers.
- Field recordings of sources which underlie much of modern music such as the American and European folk traditions.
- Speeches & spoken words of historical figures, Queen Victoria, Churchill, Roosevelt…
- Early radio broadcast transcriptions.
- Live performances and events.
- Early technical tests and experiments on recording methods.
- Public and private dictation and monitoring records, intelligence, and Presidential sources
- All commercial record releases

In many cases these records are physically compromised due to wear and age or are considered too delicate to play with normal means – contact with a phonograph stylus (needle). The archives want to both preserve these recordings, to meet the needs of any future interest, and to create broad digital access to the collections. In recognition of this, the U.S. Congress enacted the **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). Thus, recorded sound preservation is a matter of national policy in the United States. In this context, the Library of Congress is now operating the new National Audio Visual Conservation Center, a state-of-the-art facility to hold and preserve its entire collection, located in Culpeper, Virginia.

The preservation challenge for mechanical recording media revolves around its fragility and pre-existing wear or damage. The access challenge is to find an efficient way to massively transfer hundreds of thousands of discs, or other media, to digital form. In Berkeley we are addressing both these challenges by applying non-contact optical technologies and data analysis methods to the digitization and restoration of historical recordings. This research has been recognized and supported by major public and private institutions with a stake in various aspects of recorded sound history and scientific research (listed at the end of the text). Optical methods protect the samples from further damage and can circumvent many aspects of pre-existing damage. These methods are readily automated and allow the offloading of many aspects of the transfer process to software. This represents a viable mass digitization strategy.

The basic idea of the Berkeley approach is to create a high resolution digital map of the surface of the sound carrier (disc record, wax cylinder, etc.). Given this map, image processing methods can be applied to overcome the effects of wear or damage, and the stylus motion can be digitally emulated. By calculating the motion of a virtual stylus moving through the map the audio content can be reproduced.

The Berkeley technology makes use of the following methods, some of which are also evolving dramatically, as they are important for many other commercial applications.

- Electronic Imaging: the use of photo-sensitive electronic sensors to acquire images and make them available to a digital computer.
- Image and Signal Processing: the use of computers to mathematically analyze and alter images and waveforms represented in digital form.
- Optical Metrology: the use of electronic imaging, image processing, and precision motion control to derive quantitative information about the size and shape of physical objects.
- Machine Vision: a set of processes utilizing electronic imaging, processing, and metrology methods to recognize, classify, and analyze the geometry of real objects.

For the application to audio reconstruction, the implementation of these methods is novel.

The advantages and key attributes of the optical recovery process can be summarized as follows.

- Delicate samples can be played without further damage.
- Effects of damage and debris (noise sources) can be reduced through image processing since they can be objectively recognized as not matching the known shape of the groove. Thus, these discrete noise sources are resolved in the “spatial domain” where they originate and need not be considered as random effects in an audio waveform.
- Scratched regions can be interpolated.
- Dynamic effects of damage (skips, ringing) are absent.
- The method is largely independent of record material and format – wax, metal, shellac, lacquer etc. can be measured with the same procedures.
- Classic distortions and systematic errors (wow, flutter, tracing and tracking errors, pinch effects etc.) are absent or removed as geometrical corrections.
- No mechanical method is needed to follow the groove.
- Certain broken samples can re-assembled and played back.
- The acquired image data can be used to analyze the physical condition and characteristics of the sample such as groove width, defect rate, and other statistical quantities.
- Optically scanned data can be analyzed and archived as simple digital sound files (.wav etc) just as in any normal audio transfer process. In additional the high resolution digital images can be archived as standard image data for future re-analysis. No special formats or media are required.

There are two basic formats for historical sound recordings and these are explained in Figures 1 and 2. The earlier cylinder format used a groove which undulates vertically out of the surface.

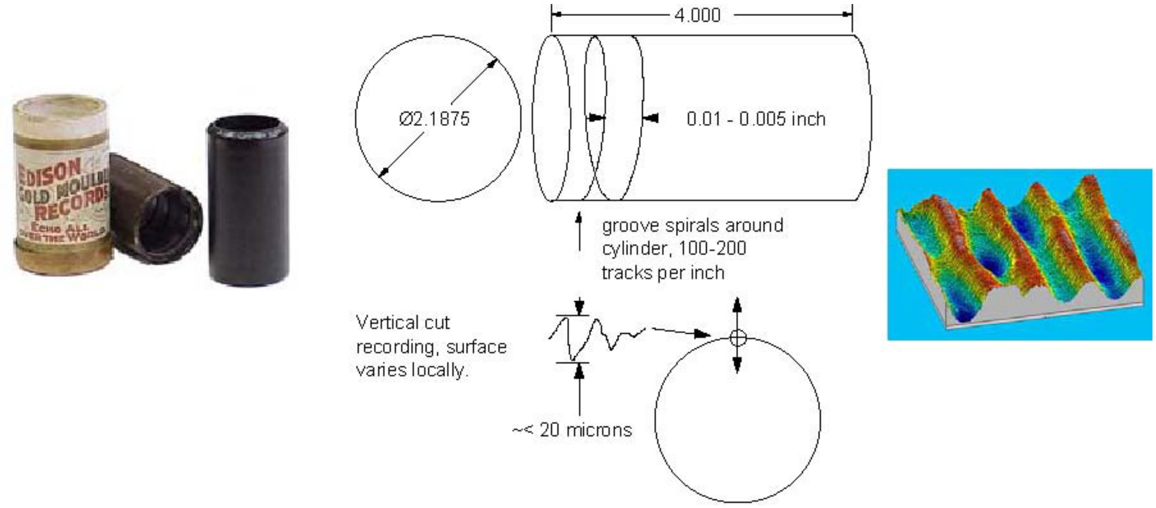

Figure 1: Edison cylinders, composed of wax or plastic carry sound in a helical groove which undulates vertically, normal to the surface. An (approx) 1 x 1 mm section is shown at right. The stylus rides in the valleys.

Figure 2: Historical disc records, composed of shellac, wax, plastic, lacquer, or metal carry sound in a spiral groove which undulates laterally in the surface plane. Typical groove width is 150 microns

The later disc format (which represents most of the archival holdings) employed a groove which undulated laterally in the plane of the disc.

There are two specific implementations of the Berkeley technology under development. One addresses high speed capture of disc media and the other, higher resolution capture of cylinders, and certain discs.

The high speed disc capture approach is explained in Figure 3. The basic research and development of this was carried out in Berkeley in 2002-2004 and published [1]. In early 2005 the National Endowment for the Humanities (NEH) approved and funded the IRENE project to develop a system for high speed disc capture for use at the Library of Congress, based upon the Berkeley research. This system was built in Berkeley and installed at the Library of Congress in August of 2006 for evaluation (Figure 4). In 2009 the system was moved to the NAVCC in

Culpeper, Va. for production testing. The imaging is based upon high resolution digital micro photography and captures a two-dimensional (2D) representation of the disc surface.

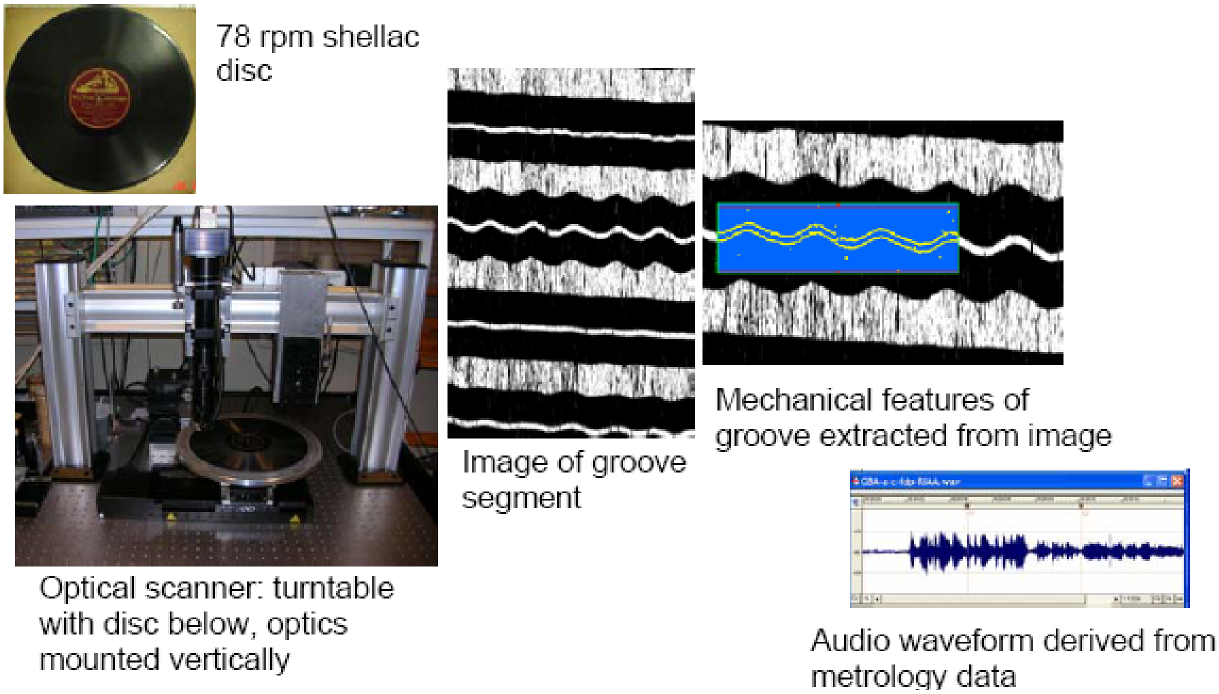

Figure 3: Depiction of the 2D scanning method used for lateral disc records (IRENE project).

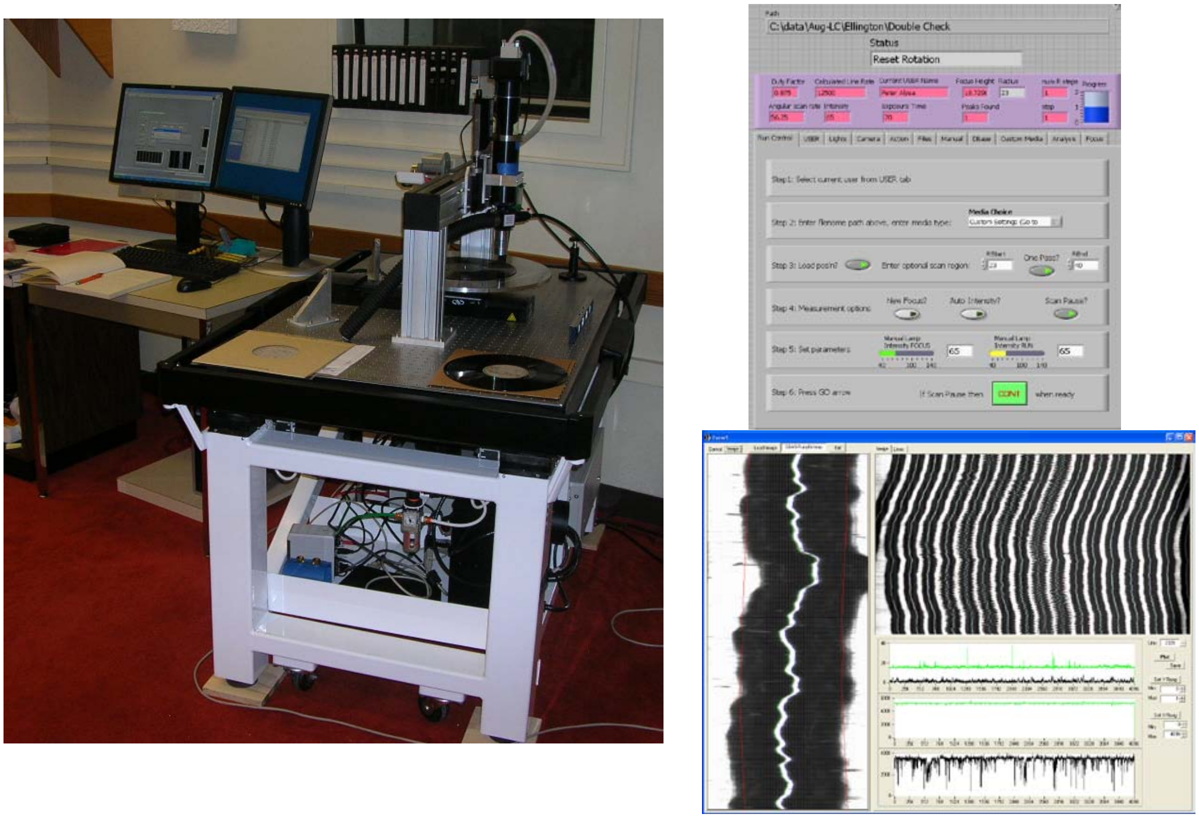

Figure 4: IRENE as installed at the Library of Congress. Insets to the right show the graphical user interface (top) and the data analysis display (bottom).

In order to measure media, such as cylinders, with a vertical groove modulation, a full three-dimensional (3D) surface profile is required. This is also the case if the full profile of a lateral groove is to be measured. With initial support from the Library of Congress and the National Archives and Records Administration, technology to address this has been under study since 2004. To profile a surface, confocal microscopy is used. While this allows for very high resolution in the vertical direction, until recently it was not a high speed process. Recent innovations in surface profiling technology, driven by commercial needs, have dramatically improved this approach. Full 3D surface profiling is now a high speed measuring method as well. Full surface profiling represents the ultimate preservation strategy since the all aspects of the surface are sampled. Figure 5 explains the 3D surface profiling approach. The basic method has also been studied, demonstrated, and published [2]. With the installation of 2D disc scanning (IRENE) at the Library of Congress complete, it became appropriate to move the 3D scanning for cylinders and discs into a form where it can be evaluated at a major archive and/or on an important collection as well. Support for the further development of 3D scanning was awarded in 2007. In April 2007 the Office of the UC Berkeley Vice Chancellor for Research granted the effort support to perform a small pilot digitization study on ethnographic cylinders from the Phoebe Hearst Museum of Anthropology. In September 2007 the project received a major two year grant from the federal Institute of Museum and Library Services (IMLS). The IMLS grant supported the development and evaluation of a full 3D scanning system for discs and cylinders.

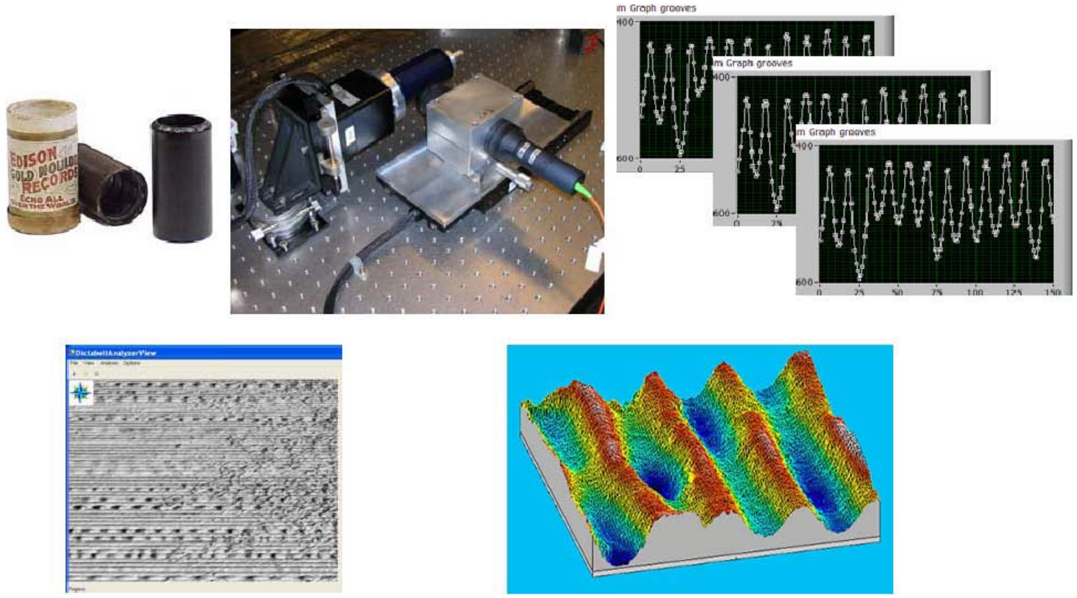

Figure 5: Depiction of the full 3D surface profiling approach. Upper-center shows the scanning instrument utilizing a confocal probe and precision motion control. Successive scans of the surface are at upper right. The vertical axis indicates depth, and the horizontal axis is along the cylinder length. Typical groove depths (widths) are 10 (250) microns. Lower plots show composite images of the measured surface.

A variety of measurements and sound reconstructions have been performed with the Berkeley technology. These can be accessed at the project website [3] where presentations are also posted [4]. As an example of a reconstruction, Figure 6 shows an audio waveform measured with the optical method, and with a stylus and turntable.

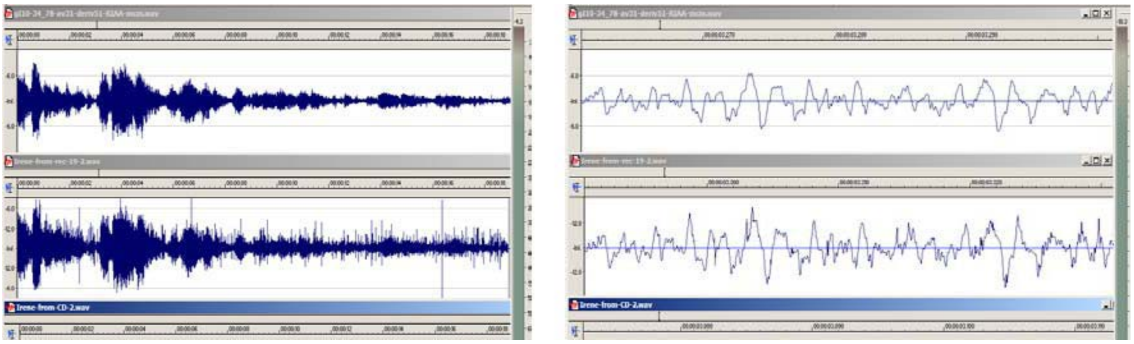

Figure 6: Audio waveform measured optically (top) and with a stylus and turntable (bottom) from the same 50 year old 78 rpm phonograph record. Left plots are on a ~20 second time scale, right plots are 40 milliseconds in duration. Note clear reduction of noise spikes due to processing and clean-up of acquired images.

In 2008, a unique and exciting opportunity for the project arose when a number of recordings made Leon Scott de Martinville, prior to Edison's invention, were found, in an archive in France. These were paper tracings of audio waveforms (see Figure 7) which were not intrinsically suitable for playback. The tracings were digitized and passed through the IRENE algorithm resulting in clearly recognizable speech, the earliest examples known of recorded sound [5].

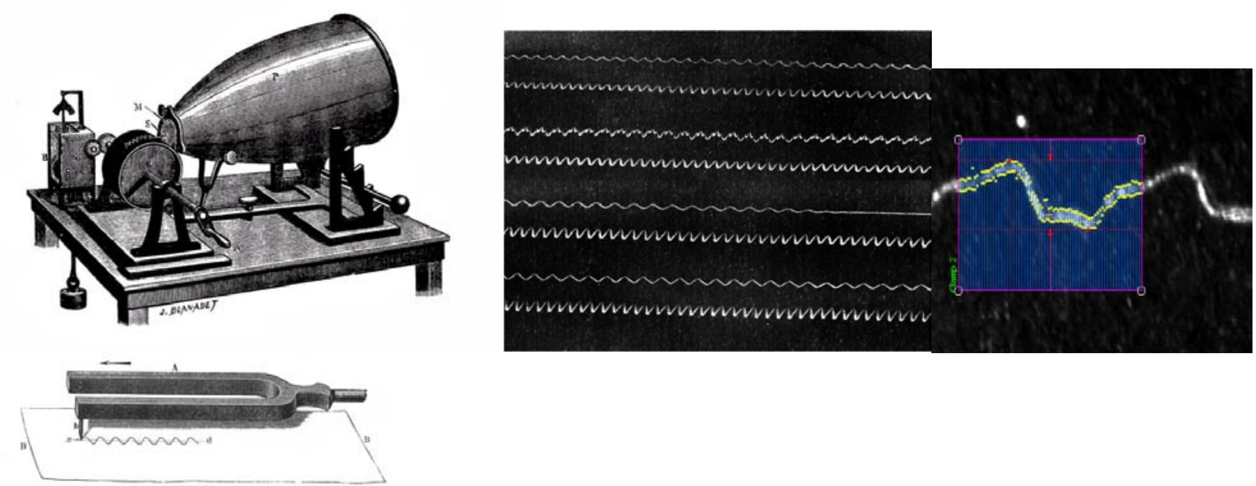

Figure 7: Upper left is the "phonautograph" built by Leon Scott de Martinville in the 1850's. Center shows a tracing on blackened paper. For each pair of traces, the upper trace is recorded audio while the lower trace is a timebase measurement from a tuning fork (lower left) vibrating at 250 cycles per second. Such images may be analyzed using the IRENE algorithms (right) in order to extract the audio content. See example links listed below.

The IMLS 3D development grant ended in 2009 with the installation of a 3D scanning system at the Library of Congress. That effort succeeded in demonstrating a 3D scanning system for cylinders which digitized a full recording in 20-30 minutes. Considerable progress was also made evaluating 3D scanning on discs. Following up on the 3D grant, IMLS awarded the project a second 3 year grant based upon the proposal "Advancing Optical Scanning of Mechanical Sound

Carriers: Connecting to Collections and Collaborations". The goals of this effort, which is currently ongoing, are two fold. The first part is bring both the 2D and 3D scanning technology into contact with collections both at the Library of Congress and more remotely. A relatively portable scanning system has been constructed for use in a disc transfer project in India. The second part is to carry out a series of special projects on small collections or items of particular interest. Included here are studies of copper galvano (negative) cylinders, fieldwork cylinders, broken cylinders and discs, and early experimental recordings produced by Alexander Graham Bell and Charles Sumner Tainter at the Volta Laboratory, in Washington, D.C. in the 1880's. Some examples of these special materials are shown in Figures 8 and 9.

Figure 8: From the left (a) Greyscale (depth) image from Hearst Museum wax cylinder showing clear damage from fibers on the surface (~1910). (b) Example of experimental Bell recording, wax on paper, from the Smithsonian (early 1880's) (c) Example of copper cylinder galvano mold from the Berlin Phonogramm Archive (early 20th century). (d) The Dickson Cylinder from the Edison National Historic Site, first film soundtrack experiment (1893).

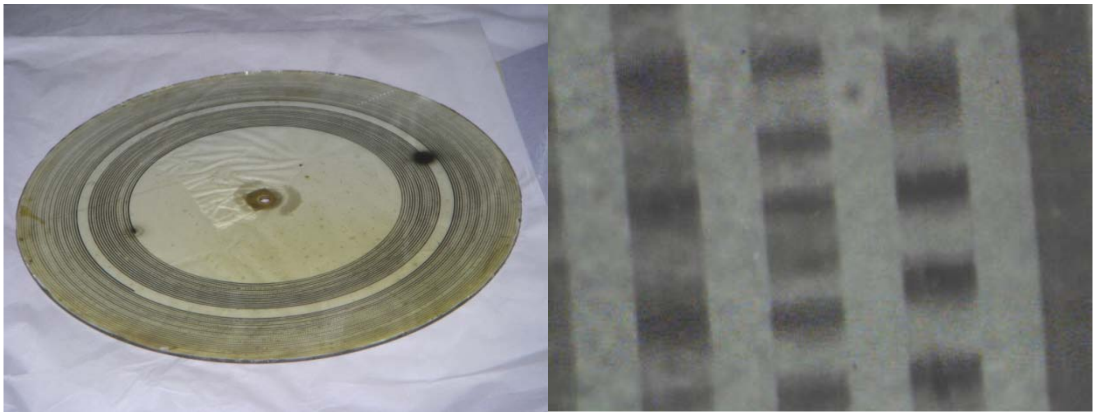

Figure 9: Experimental Bell-Tainter photographic recordings, Smithsonian Institution. Media consists of a glass disc sensitized with emulsion, exposed to a sound actuated light source, early 1880's.

The special collections studies are a unique opportunity to enlighten the early inventive period in the history of sound recording and to create new access to materials of particular interest to the research community.

Archivists have estimated that of order 1 million recordings could benefit from the Berkeley technology. According to Peter Alyea of the Motion Picture, Broadcast, and Recorded Sound Division of the Library of Congress, "The solution to (the challenges of preservation and access) is to innovate in the area of reformatting technology. The Berkeley (technology) marks a major change in the history of audio technology and its relationship to the field of preservation. Rarely have audio archive specialists worked directly with scientists to address and solve specific audio preservation problems through the development of preservation targeted technology. The technology is non-invasive, posing no risk to the source media, can reproduce broken and otherwise damaged discs, and will not require trained specialists to perform the work. The system can reproduce sound that could not be extracted through traditional physical methods by examining and utilizing the complete surface of the groove walls to generate the audible output. Furthermore, statistical information can be derived from a vast number of discs to study idiosyncracies of different disc cutting and pressing techniques, and wear patterns.

With more than a century rich with commercially produced and unpublished sound recordings of music, poetry, drama, literature, and story-telling, and radio broadcasts capturing speeches, entertainment, and news, we can not afford to lose this cultural resource. I expect the Berkeley (technology) to revolutionize the archival field and ensure that we do retain our recorded sound heritage."

A compelling example of a collection which could uniquely benefit from this technology is the Native American fieldwork recordings. Starting in the late 19th century, anthropologists, linguists, and ethnographers used the new Edison soft wax cylinder recording systems to create in excess of 10,000 recordings. Most of these currently reside in a few major archives including the Library of Congress, the University of California Phoebe Hearst Museum, and the Indian University Archive of Traditional Music. The results of this research could lead to a future non-invasive digitization project which could significantly improve restoration of and access to these materials on a large scale. These early recordings of Native American languages are of immense interest to native communities, linguists, and anthropologists, because in many cases the genres and styles recorded 100 years ago are no longer in active use or clearly remembered, and in some cases these recordings are our only audio record of entire languages that have become extinct. At the Hearst Museum, for example, some of the recordings were mastered onto reel-to-reel tapes over 40 years ago with generally poor results and the possibility of greatly improved copies of these recordings would be of great value to scholars and indigenous communities. To date, the Berkeley project has collaborated with the Burke Museum at the University of Washington, and the Indiana University Archive of Traditional Music to digitize some 24 cylinders recorded in the early 1930's by anthropologist Franz Boas working at Fort Rupert on Vancouver Island with the Kwakiutl community.

This development of this technology is a good example of how the methods of the physical sciences can be brought to bear on problems facing other fields of research and culture. In the past, the humanities and the sciences and engineering have intersected with great benefit. Examples include the use of radioactive dating and spectroscopy in archeology and art history, the use of digital signal processing and computation is the analysis of musical scores and the creation of new music and musical forms, and the entire field of photography, image acquisition, storage, and permanence. These efforts are exciting and inspiring for students who have, and will continue to, participate in their development. Cultural materials in the audio collections may come from communities which have been historically under-represented in science and engineering. These developments may serve to draw students from those communities into research academically, or as a career. As an example for use in educational outreach for both the physical sciences and the humanities, this research, and the topic of historical sound recordings have a broad and deep appeal to the public.

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The University of California at Berkeley
The Department of Energy
The Mellon Foundation
The John Simon Guggenheim Memorial Foundation
The Smithsonian Institution

References

[1] V.Fadeyev and C. Haber, **J. Audio Eng. Soc**., vol. 51, no.12, pp.1172-1185 (2003 Dec.).
[2] V.Fadeyev et al, **J. Audio Eng. Soc**., vol. 53, no.6, pp.485-508 (2005 June).
[3] http://irene.lbl.gov/
[4]Recent presentation at the Library of Congress: http://irene.lbl.gov/LC-TOPS-2010-Save.pdf
[5] http://en.wikipedia.org/wiki/Leon_Scott

Selected Media and Other Coverage
KQED television QUEST report:
http://www.kqed.org/quest/television/how-edison-got-his-groove-back

Video of a presentation at UC Berkeley: http://www.citris-uc.org/CRE-Oct18-2006

In late 2007 and early 2008 we were involved in a project to restore the earliest sound recording in history. This was a "phonautograph" paper recording due to French inventor Edouard-Leon Scott de Martinville. This work is addressed recent posted presentations at http://irene.lbl.gov/ (Fermilab 10-8-2008 and Adobe 3-3-2009). For additional information see these links.

FirstSounds Collaboration
NY Times March 27, 2008
National Public Radio Report

Other media
Recent NPR Morning Edition piece:
http://www.npr.org/templates/story/story.php?storyId=11851842

Early coverage from 2004 when the research was first funded
Berkeley Science Review
http://sciencereview.berkeley.edu/articles.php?issue=7&article=briefs_5
The New York Times
http://www.nytimes.com/2004/05/06/technology/circuits/06next.html?ex=1399176000&en=e166a1f50fe6725f&ei=5007&partner=USERLAND
The BBC
http://news.bbc.co.uk/2/hi/uk_news/magazine/3917849.stm

Canadian Broadcasting Company
http://www.cbc.ca/quirks/archives/03-04/may15.html
The San Francisco Chronicle
http://www.sfgate.com/cgi-bin/article.cgi?file=/c/a/2004/07/12/MNGJP7JRC21.DTL

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