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Author(s): David Cooper and Ian Sapiro

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Ethnomusicology in the Laboratory: From the Tonometer to the Digital Melograph

David Cooper and Ian Sapiro

Ethnomusicologists have often been in the vanguard in the employment of technology in their research, whether the phonograph, reel-to-reel tape, audiocassette, DAT, minidisk or hard-disk-based device. More recently, technoculture itself has become the focus of ethnomusicological study in a volume edited by Lysloff and Gay in 2003. In this paper we explore the historical background to some of the early technologies for automatic transcription, which were developed for, or adapted to serve the purposes of, the ethnomusicologist. We suggest that the software Praat, *a program designed for the analysis and synthesis of speech, has the potential to replace the various custom-fabricated devices labelled melographs, and we illustrate some of its capabilities through a brief discussion of its application to a song recorded by the north Ulster musician, Joe Holmes.*

Nazir Jairazbhoy has noted that "if a recording is transcribed by an automatic device, it may make a more or less 'objective' statement (within its own technical limitation), but only about a subjective recorded impression of an exceedingly complex original" (1977, 264). Although we propose *Praat* as a useful technology for the ethnomusicologist, we share Jairazbhoy's concerns about the conceptual limitations of "scientific measurement", and endorse his conclusions that:

> The primary value of automatic transcriptions would be to throw light on what we do *not* "hear", what we change in the process of "hearing", or what we take for granted. They can also provide an insight into some of the extremely subtle elements of music which we cannot readily distinguish aurally, but which might nevertheless influence our perceptions on a subconscious plane. They can provide us with acoustical standards against which we could compare the effect of auditory and cultural responses. (Jairazbhoy 1977, 270)

David Cooper is Professor of Music and Technology in the School of Music at the University of Leeds. Email: d.g.cooper@leeds.ac.uk. Ian Sapiro is a research assistant in the School of Music at the University of Leeds, currently undertaking research on the film music of Trevor Jones. Email: i.p.sapiro@leeds.ac.uk

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Early Devices for the Subjective Measurement of Frequency

In 1834, the German acoustician Johann Heinrich Scheibler detailed a device utilizing an array of 54 tuning forks each separated by 4 Hz from its neighbour, and covering the range from 220 to 440Hz, to assist in the *subjective* measurement of pitch. Anton Appunn's later invention, the more sophisticated *Appunn Tonometer*, employed 64 reeds like those found in an accordion or a harmonium, tuned in 4 Hz increments from 256 Hz to 512 Hz, the air flow being controlled by a simple bellows system (Stone 1879, 102). To determine a sound's frequency, the operator would play a phonograph recording and hold the reproducer against the wax cylinder by hand so that a short section could be repeated, or in more modern terms, "looped", while searching for the reed with the closest frequency (the one at which beating was minimized). Such a technique clearly depended on the aural acuity of the operator, but the results produced were of considerable value in providing evidence for intonational fluctuations in performance, as demonstrated, for instance, by data from Erich von Hornbostel's analyses of phonograph recordings of Irish folksongs in Richard Henebry's *A Handbook of Irish Music* (1928).

The Phonodeik

The Tonometer offered neither a fully "objective" nor an automated means of transcribing frequency. Fourier analysis of graphs of waveforms could give much greater precision and consistency, but if the mathematical calculations were done by hand, they proved immensely laborious. Mechanical harmonic analysers (for example, the machine developed by Olaus Henrici towards the end of the 19th century) simplified the process, but only if images of the waveforms were scaled to sufficiently large dimensions (around 16 inches) for the apparatus to function properly.

To produce the image of a waveform for analysis, it was necessary to turn to a device such as the phonodeik, developed by Dayton Clarence Miller.[1] In *The Science of Musical Sounds*, Miller explained the function of the phonodeik, which was effectively a prototype storage oscilloscope (1916, 79–82). It employed a resonator horn (rather like that found in a phonograph) with a very thin glass diaphragm mounted at its narrow end. A tiny mirror was attached to the diaphragm by means of a spindle and this rotated in sympathy with the sound vibrations entering the horn. A beam of light focused on the mirror was deflected in proportion to the motion of the mirror and the visual representation of the sound wave this produced was recorded on film. The mirror assembly behaved like an amplifier, magnifying the signal some 2500 times, and the photographed output was supplemented with a reference "time signal" from a stroboscopic tuning fork vibrating at 100 Hz, as well as a zero crossing axis. Miller's system offered a relatively simple and accurate means of automatically recording waveforms – the time-domain representations of audio signals – and thus the potential to measure their fundamental frequency.

Metfessel's Phonophotography

For his study of African-American songs, *Phonophotography in Folk Music: American Negro Songs in New Notation* (1928a), Milton Metfessel adopted a technique closely related to Miller's, but using the phonelescope developed by Herbert Grove Dorsey rather than the phonodeik. This similarly translated the motion of a diaphragm into a waveform trace by means of a mirror whose movements were mechanically synchronized to those of the diaphragm (Dorsey 1922). In Metfessel's phonophotographic experiments, three traces similar to those discussed above were recorded synchronously onto moving film (1928a, 22–3), and the frequency of the sound wave was manually calculated from the film by measuring the wavelength of the vocal sound wave on the film with a ruler and comparing it with the 100 Hz reference.[2]

Metfessel regarded Miller's approach as both very expensive and labour intensive, "a record of five minutes of singing requiring film costing about fifty dollars, with the measuring and graphing of the waves requiring from one hundred to three hundred hours, depending on the desired detail of the measures" (1928b, 431); this evaluation was, presumably, equally applicable to his own experimental work for *Phonophotography in Folk Music*. Stroboscopic methods, such as the tonoscope, were also problematic, for "while serving many purposes, [they] do not give a continuous record of the rate and form of important patterns of singing and speaking, to say nothing of the time this method requires to transcribe a song accurately" (1928b, 431).

Metfessel responded to these technical difficulties by devising a novel method based on the stroboscope, which simultaneously acquired the signal and recorded it onto photographic film, in ideal circumstances permitting the direct display of the pitch of a sound. The technique (schematically illustrated in Figure 1) involved the modulation of a light source (a neon tube) by the audio signal under investigation,

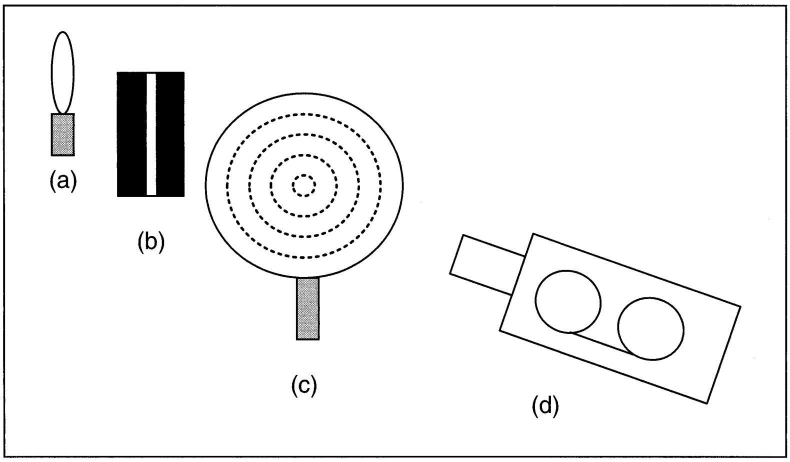

Figure 1 A Schematic Diagram of the Elements of Metfessel's System: (a) Flashing Neon Lamp, (b) Slit, (c) Rotating Disc and (d) Camera.

which generated a flashing light at twice the rate of the fundamental frequency. A rotating disk or drum had tiny holes cut into it spaced such that, when the frequency of sound matched the rotation rate and spacing of the holes, a bright flash of light would be emitted from the appropriate hole in the row or circle of perforations. If a revolving drum was used, the holes would be in equally spaced rows, each row representing 1/5 of a semitone in the illustration provided by Metfessel in his article. If a disc was used, the perforations were placed in a series of concentric circles. A plate with a narrow slit was sited between the light source and the perforations on the drum or disc, to ensure that the light was transmitted to only a single column of holes. The resulting flashes were recorded on a continuous film in a camera, creating a line which followed the pitch contour of the melody.

In the example that Metfessel provides of the output from his system, the melodic line appears as the middle of three dotted tracks, the outer two being artefacts generated by the system.[3]

Seashore's Phonophotograph

The music psychologist Carl Seashore's "phonophotograph" included certain refinements of Metfessel's approach, while retaining the same underlying principles (Tiffin 1932). The most important addition was an "intensity curve" – effectively a graph of the mean-square pressure changes in the waveform which could be regarded as a measure of subjective loudness (Tiffin 1932, 126). To produce this trace, the microphone was connected to an amplifier whose output was rectified (by converting the signal from alternating to direct current). The signal was then passed to a condenser and choke coil which smoothed it so that it varied in proportion to the mean square amplitude of the wave and this was recorded on the film, overlaid with lines separated by one decibel as references.

Obata and Kobayashi's Direct-Reading Pitch Recorder

In the late 1930s, the Japanese physicists Jūichi Obata and Ryūji Kobayashi reported a direct-reading pitch recorder which they claimed was applicable to the analysis of both music and speech (Obata and Kobayashi 1937, 1938). Their frequency meter was derived from the work of Albert W. Hull and Frederick Hunt and involved a very different principle from those outlined above, a "double-tube thyratron inverter" forming the heart of the apparatus (Hunt 1935), and outputting a signal whose current was directly proportional to the frequency of the input.[4] Other circuits were responsible for "conditioning" the input by filtering it (the wave form adjuster and the smoother), constraining and adjusting its amplitude changes (the automatic volume control and the amplifiers), and displaying it (the oscillograph) (Obata and Kobayashi 1937, 157).

The direct output of the thyratron-based circuitry offered a step change in frequency measurement, as it was near-instantaneous in response and did not require a mechanical connection to the source or the mediation of film. The limiting factor in its application was its response to complex waveforms which repeatedly changed from positive to negative within a single period, and of course, like all the other devices under discussion here, it was restricted to monophonic signals.

Seeger's Melographs

Charles Seeger designed several pitch-tracking devices specifically for research in comparative musicology, which he dubbed melographs. He had considered the possibility of an "instantaneous music notator" in a paper presented to the Third Conference of the International Folk Music Council held in 1950 at Indiana University, Bloomington (Seeger 1951), describing an experimental set-up (Figure 2) that he and his son, Charles L. Seeger (an astronomy professor), had assembled in the latter's radar-astronomy laboratory at Cornell University (Seeger 1951, 104).

Crude as this assembly was, it proved a proof of concept, and Seeger went on to specify three models of melograph, the first of which (Model A) was custom designed by Dr V. C. Anderson and built by the Research Manufacturing Corporation of San Diego (Seeger 1957, 63). Model B offered some refinement while employing the same basic principles, but it was with Model C that Seeger achieved a significant advance, for this was a much more complex device, able to display spectral data in the form of a spectrogram as well as frequency/pitch and intensity (Hood 1982 [1971], 94–7). Ironically, it was later dismantled for spares when sent to the physics department for an estimate for repairs (Hood 1979, 78). Devices similar to Seeger's melographs were later developed at Uppsala University, Sweden (Tove et al. 1966) and the Hebrew University, Jerusalem (Cohen and Catz 1968).

Implementing the Melograph Using *Praat*

Pitch-tracking algorithms which identify the fundamental frequencies of musical tones lie at the heart of computer applications for automatic transcription of melody, and several different approaches to the analysis of monophonic signals have been implemented. In the time-domain, these algorithms have hitherto involved such

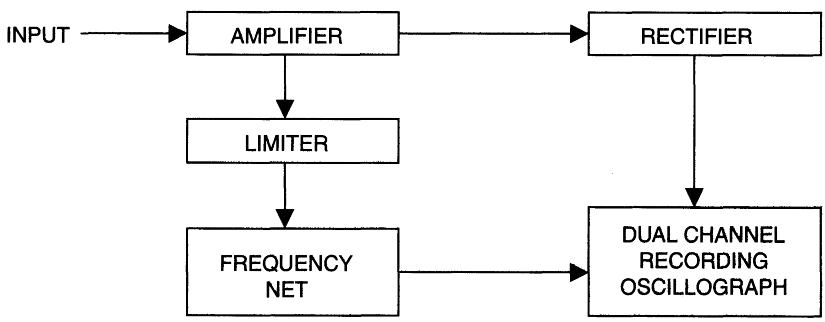

Figure 2 Block Diagram of the Prototype Device Assembled by Seeger.

techniques as zero-crossing counting of low-pass filtered signals, autocorrelation and shape modelling (Cooper and Ng 1996), and, in the frequency domain, Fourier analysis, phase vocoding (Bailey and Cooper 2000) and wavelet analysis. A number of the individual processes can be found in hard-disk editing programs (FFT-based spectral analysis and filtering) and transcription software (monophonic pitch tracking normally directed towards MIDI output). However, few if any of the readily available programmes provide the ethnomusicologist with the facility to emulate and expand the approach taken in the melograph.

Praat is a computer program developed by the Dutch academics Paul Boersma and David Weenink at the Institute of Phonetic Sciences at the University of Amsterdam. Although intended for the scientific study of speech sound, it has a rich feature set that provides for frequency and intensity tracking, and spectral analysis, as well as facilities for the recording, processing, statistical analysis and modelling of sound files, which make it potentially useful for ethnomusicological research.[5] It is open source and binary executables are freely available for the Mac, Windows and Linux operating systems under the GNU General Public License.

Background to Praat – The User Interface

There are four basic windows in the *Praat* user interface: an object window where most of the signal input, generation and processing are performed; various editor windows where signals are displayed and manipulated; a picture window in which graphs are created and saved in formats such as windows metafile and encapsulated postscript; and a help/manual window. The following discussion focuses on the aspects of *Praat* that are particularly relevant to the use of the software as a melograph, and many of its other useful features (such as the built-in statistical functions) are ignored.

The Object Window

The object window contains four menus – Praat, New, Read and Write. Audio files in WAV, AIFF or AIFC, NEXT/Sun AU or NIST formats (the latter being in use in the speech research community) or raw data are opened from the Read menu. The two channels of stereo files can be loaded as separate objects and "long files" can be read into special *Praat* objects.

The Editors

Once loaded as an object, the sound file can be viewed in the *Praat* editor by selecting the Edit button at the right side of the object window. This places the data into the relevant editor and displays the time-domain representation of the waveform in the upper section of the window. Depending on the settings adopted, the lower part of the window may display any combination of the spectrum (as a spectrograph), the pitch contour and the intensity contour. It is also possible to display a formant contour – the trajectory of the various formant frequencies (the peaks of resonant frequency which characterize the vocal tract) of a sound.

The pitch contour might be of immediate interest to the ethnomusicologist, and several parameters may be adjusted to improve the resolution and accuracy in the Pitch menu. The basic pitch-tracking algorithm involves an enhanced autocorrelation technique devised by Boersma (1993) which compensates for adverse effects of windowing the signal. When the settings menu item is selected, a dialog box opens which offers the user options to select the pitch range (50–500 Hz is likely to be sufficient for most male voices, 150–1000 Hz for most female ones) and the display units (Hertz, Hertz logarithmic, Mel, Erb and Semitones re 100 Hz). Of these, Hertz logarithmic is generally the most appropriate for displaying a melodic outline in a musically meaningful way.

Options in the advanced settings menu item provide a further level of sophistication. Several of these are specifically intended for speech processing: for example, the parameter Voicing Threshold assists the discrimination of unvoiced components (where the vocal cords are not vibrating); and Voiced/Unvoiced Cost is concerned with the judgement of transitions between unvoiced and voiced elements. Two parameters are specifically associated with octave selection: Octave Cost provides for the selective favouring of higher frequency candidate fundamentals over lower ones; and Octave Jump Cost offers a means of reducing or increasing large frequency changes (the larger the value, the fewer the large leaps detected). Setting a Silence Threshold compensates for a noisy signal and the Very Accurate setting invokes the application of a longer Gaussian window rather than a shorter Hanning window to the signal under investigation. (Windows in this context refer to mathematical functions, which are multiplied by the signal to improve the resolution of the analysis.)

When a pitch contour has been generated, it may be interrogated, and the frequency at any position revealed simply by moving the cursor to the point of interest on the pitch contour. The minimum or maximum frequency in a selection may similarly be obtained by selecting the relevant menu item, and the time and frequency components of a segment can be copied as text to a text editor window where they may be saved or examined. The pitch contour can itself be saved as a pitch object (a further standard *Praat* object) in the object window by selecting the Extract Visible Pitch Contour menu item from the Pitch menu. This pitch object can be re-synthesized and played, or further modified by editing it in a special Pitcheditor window. It can also be converted to a pitchtier object – a time-stamped pitch contour convenient for external manipulation in a spreadsheet programme (see Table 1). Like many of the other *Praat* objects, pitch and pitchtier objects can be drawn as graphs by selecting the Draw button in the object window. The resulting picture (displayed in the Picture window) can be saved as a metafile or as encapsulated postscript.

Pitch objects can also be directly created from a sound file in the object window using the Analyse Periodicity button and selecting To Pitch ... from the resulting

Table 1 Sample Time and Frequency Data Saved in Spreadsheet Format from a Pitchtier Object; the First Column Gives the Time Position in Seconds and the Second, the Frequency in Hertz.

1.38	135.335838
1.39	135.051492
1.40	133.0922
1.41	136.485203
1.42	136.902571
1.43	136.812381
1.44	135.889943
1.45	134.345813
1.46	132.687493

drop-down menu. Equally, Intensity and Spectrogram objects can be produced from either the editor window or the object window, and their outputs saved as picture files (see Figure 3) or data that can be loaded into a spreadsheet application such as Excel.

Although the frequency output in Table 1 is displayed in Hertz, this can be converted to cents (1/100 of an equal tempered semitone) by applying the appropriate formula to the pitchtier. Pressing the Modify button in the object window reveals a series of options from which Formula is selected. A series of frequencies in Hertz can be converted to cents by entering the following:

$$F_c = \frac{\ln(x/f_{ref})}{\ln(2)} * 1200$$

where, F_c is the frequency in cents, x is the frequency in Hertz, f_{ref} is the frequency reference against which frequencies in cents are calculated, and ln() is the natural log function.

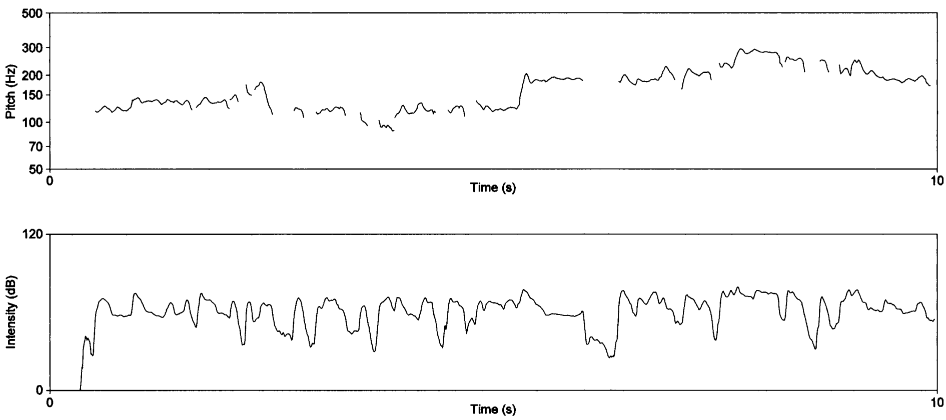

Figure 3 A Praat Picture Saved as Encapsulated Postscript File of the Pitch and Intensity Contours of a 10-Second Section of a Sound File.

In *Praat*, the current frequency value is contained in the variable "self", and so the following formula should be entered:

$$((\ln(\mathrm{self}/128.0))/\ln(2))*1200$$

In this example, the reference frequency is 128 Hz (roughly C_3, the C below middle C). The resulting modified pitch tier may be drawn as a graph and exported as an encapsulated postscript file.

Using *Praat* in a Musical Context

The following brief examination of "The Maid of Mourne Shore", as sung by the Ulster fiddler and singer Joe Holmes (1906–78) and recorded by Holmes's close friend and singing partner, Len Graham, illustrates *Praat*'s utility a tool to assist in the transcription and display of monophonic melodies, as well as the discrimination of the subtle musical detail alluded to by Jairazbhoy.

Figure 4 shows four different representations (time domain, melodic contour, intensity contour and staff notation) of the second verse of the song, the upper three graphs being temporally aligned. The staff transcription smoothes out the fine detail of the performance evident in the pitch and intensity contours, most obviously in terms of timing, but as importantly in terms of melodic microstructure. Consider, for example, the segment from the first line setting the text "it was in Kilkeel town" (Figure 5).

Here the pitch and intensity curves in combination graphically display the microstructure of the performance. Thus the half-spoken "it", the melodic turn and portamento on the transition onto the word "in", the emphasis on "Kil-", "keel" and "town", and the subtle use of vibrato are more clearly set in relief. Each of these parameters can be horizontally or vertically magnified to reveal such features in finer resolution.

Quantitative data can easily be extracted from the pitch editor window, either directly by reading the value at the appropriate cursor position or indirectly through the analysis of the data representing a set of samples displayed in a pitch- or intensity-listing window. For example, taking the note sung to "town", its duration from onset to offset (1.208221 secs), the mean energy level of its intensity (70.78 dB), its average frequency (134.18 Hz), and its vibrato rate (7.14 Hz) and depth (130.24–139.62 Hz, or $+68/-51$ cents relative to the average frequency) may all be simply and accurately computed.

Conclusions

It is not our intention in this discussion to enter the debate about the advantages and disadvantages of melography or the weaknesses and strengths of such a supposedly "objective" approach. However, for those who would like to access and measure the performance data contained explicitly or implicitly within sampled sounds, *Praat* does offer a powerful and flexible tool and because it conforms to the GNU General

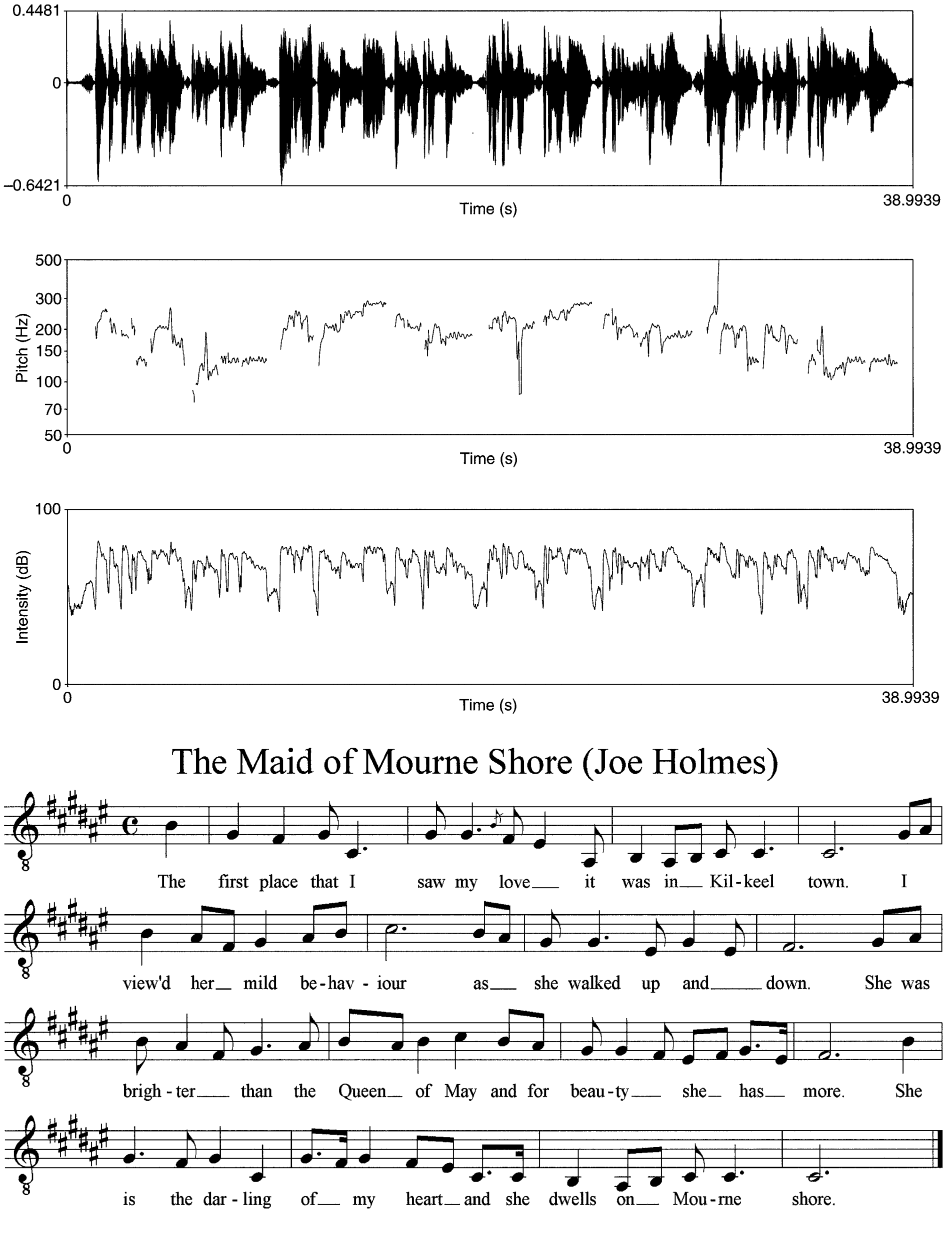

Figure 4 Verse 2 of the Song “The Maid of Mourne Shore”, Sung by Joe Holmes. The upper three graphs give the time-domain representation, and the melody as a pitch trace and an intensity trace. The transcription in staff notation is by the authors.

Public License, it could in principle be freely customized to the specific needs of an individual researcher.

It must be borne in mind that, like most such software, it is fundamentally limited to monophonic sources or polyphonic ones where the individual sources can be

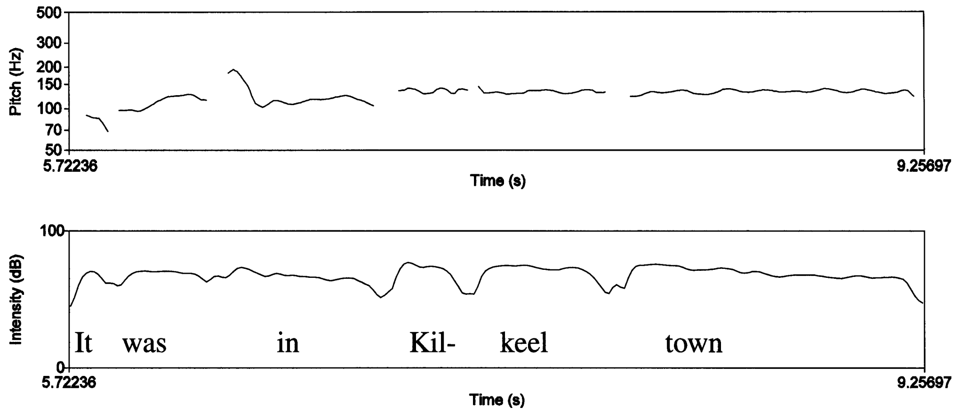

Figure 5 The Second Half of the First Line of the Second Verse of "The Maid of Mourne's Shore".

disaggregated into monophonic strands, and, although experimental work by the authors has yielded some useful results from fiddle playing that involves a fair degree of double stopping, care is needed in the setting of appropriate pitch-tracking parameter values. Some advances have been made in the engineering and computing communities in the area of polyphonic pitch tracking, but this still remains a "holy grail". In the meantime, if this limitation is accepted and if a monophonic source is available or can be extracted (for example by filtering a signal or recording), then *Praat* can prove extremely useful.

In 1951 Charles Seeger outlined his project for an "instantaneous music notator". He remarked that:

> The aim of the project is to develop an electronic device that will record instantaneously, for reading by musicians rather than by physicists, a single melodic line led into it by a wire from a phonograph or microphone. The minimum requirement is to show the functions of pitch and time by means of a single curve traced upon suitable graph paper. It is expected that dynamics can be shown, if desired, upon a separate graph – also by a single line-curve. The maximum requirement is to show not only pitch, time and dynamics (which last could also in part indicate accent) but also timbre, probably by some other medium than by an oscillographic recorder. (Seeger 1951, 103)

Seeger looked forward to the time when "the science of Comparative Musicology (hopefully renamed!) will be regarded as having become a science in two great steps – first, by the use of mechanical and electronic *sound recording in the field*, and second, by the use of mechanical and electronic *sound-writing in the laboratory*" (1951, 106). Whether ethnomusicology should be seen as a science will be a moot point for many working in the research field, but for those who are interested in applying scientific methodology to some aspects of the measurement and transcription of musical sound, technology has now matured to the point where the laboratory can fit comfortably in the backpack or the briefcase.

Notes

[1] Miller was Professor of Mathematics and Physics at the Case School of Applied Science (Case Western Reserve University) from 1895 to 1936.

[2] This also compensated for possible errors caused by the speeding up or slowing down of the camera mechanism. The relationship between the frequency to be measured and the reference is mathematically expressed as: Fsw = 100 * (Lref/Lsw) Hz, where Fsw is the frequency of the sound wave, Lref is the measured length of one cycle of the 100 Hz reference wave, and Lsw is the length of one cycle of the vocal wave.

[3] In the case of the upper trace, lying a perfect fourth above the true reading, there is a 4:3 ratio between the frequencies, and a flash will be synchronized on every fourth hole of the upper row and third hole of the lower row. Similarly there is a 5/4 ratio (major 3rd) between the correct reading and the lowest trace starting on D, which means that the flashes will be in synchronization on every fifth hole of the upper row and fourth hole of the lower row.

[4] At least for sinusoidal or near sinusoidal sound waves below 7000Hz.

[5] The software is freely available under the GNU public licence, for the Windows, Macintosh, Linux, SGI and Solaris operating systems from the researchers' website: <www.praat.org>. The source code is also available from this site.

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