Author's Notes, May 4, 2000

At the request of people involved in standards-setting for audio, who wanted this information made available as soon as possible, I published this original paper here, rather than in a professional journal.

Because I use figures 1(a,b,c) not only as data but to explain my reasoning, I include them in the paper itself. To save download time, other figures are given as links. After you look at one of these figures, your browser's "Back" button may return you to exactly where you were in the paper. If it doesn't, please note what section of the paper you are in before you link to the figure, then return by using the section links supplied with each figure.

The footnotes have links to return you to where they were cited.

All of the figures are 900 pixels wide. Viewing will be easiest on a monitor screen of 1024 x 768 or higher resolution, and with 256 or more colors.

There's Life Above 20 Kilohertz!
A Survey of Musical Instrument Spectra to 102.4 KHz

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Abstract

At least one member of each instrument family (strings, woodwinds, brass and percussion) produces energy to 40 kHz or above, and the spectra of some instruments reach this work's measurement limit of 102.4 kHz. Harmonics of muted trumpet extend to 80 kHz; violin and oboe, to above 40 kHz; and a cymbal crash was still strong at 100 kHz. In these particular examples, the proportion of energy above 20 kHz is, for the muted trumpet, 2 percent; violin, 0.04 percent; oboe, 0.01 percent; and cymbals, 40 percent. Instruments surveyed are trumpet with Harmon ("wah-wah") and straight mutes; French horn muted, unmuted and bell up; violin *sul ponticello* and double-stopped; oboe; claves; triangle; a drum rimshot; crash cymbals; piano; jangling keys; and sibilant speech. A discussion of the significance of these results describes others' work on perception of air- and bone-conducted ultrasound; and points out that even if ultrasound be taken as having no effect on perception of live sound, yet its presence may still pose a problem to the audio equipment designer and recording engineer.

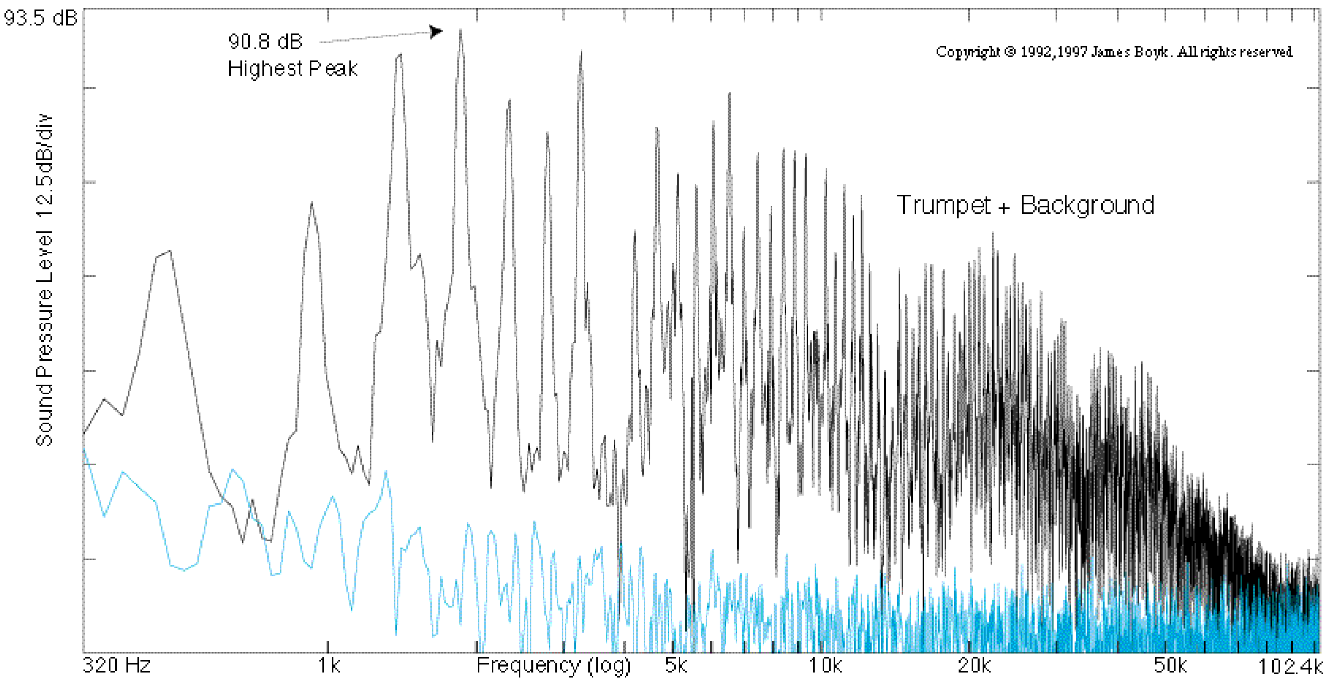

Figure 1(a) (Amplitude vs. frequency). **Trumpet with Harmon mute**; 95.5 dB at Aco 7016 microphone 4 feet away. Microphone aimed at bell, which was angled down about 20 degrees. Upper Trace: Trumpet + Background, corrected to 70 kHz (see text). Lower trace: Background alone.

I. Introduction

Each musical instrument family — strings, winds, brass and percussion — has at least one member which produces energy to 40 kHz or above. Some of the spectra reach this work's measurement limit of 102.4 kHz.

Harmonics of French horn can extend to above 90 kHz; trumpet, to above 80; violin and oboe, to above 40; and a cymbal crash shows no sign of running out of energy at 100 kHz. Also shown in this paper are samples from sibilant speech, claves, a drum rimshot, triangle, jangling keys, and piano.

The proportion of energy above 20 kilohertz is low for most instruments; but for one trumpet sample it is 2%; for another, 0.5%; for claves, 3.8%; for a speech sibilant, 1.7%; and for the cymbal crash, 40%. The cymbal's energy shows no sign of stopping at the measurement limit, so its percentage may be much higher.

The spectra in this paper were found by recording each instrument's sound into a spectrum analyzer, then "prospecting" moment by moment through the recordings. Two instruments (clarinet and vibraphone) showed no ultrasonics, and so are absent here. Other instruments' sounds extended high up though at low energy. A few combined ultrasonic extension with power.

The mere existence of this energy is the point of this paper, and most of the discussion just explains why I think that the spectra are correct, within the limits described below. At the end, however, I cite others' work on perception of air- and bone-conducted ultrasound, and offer a few remarks on the possible relevance of our spectra to human perception and music recording.

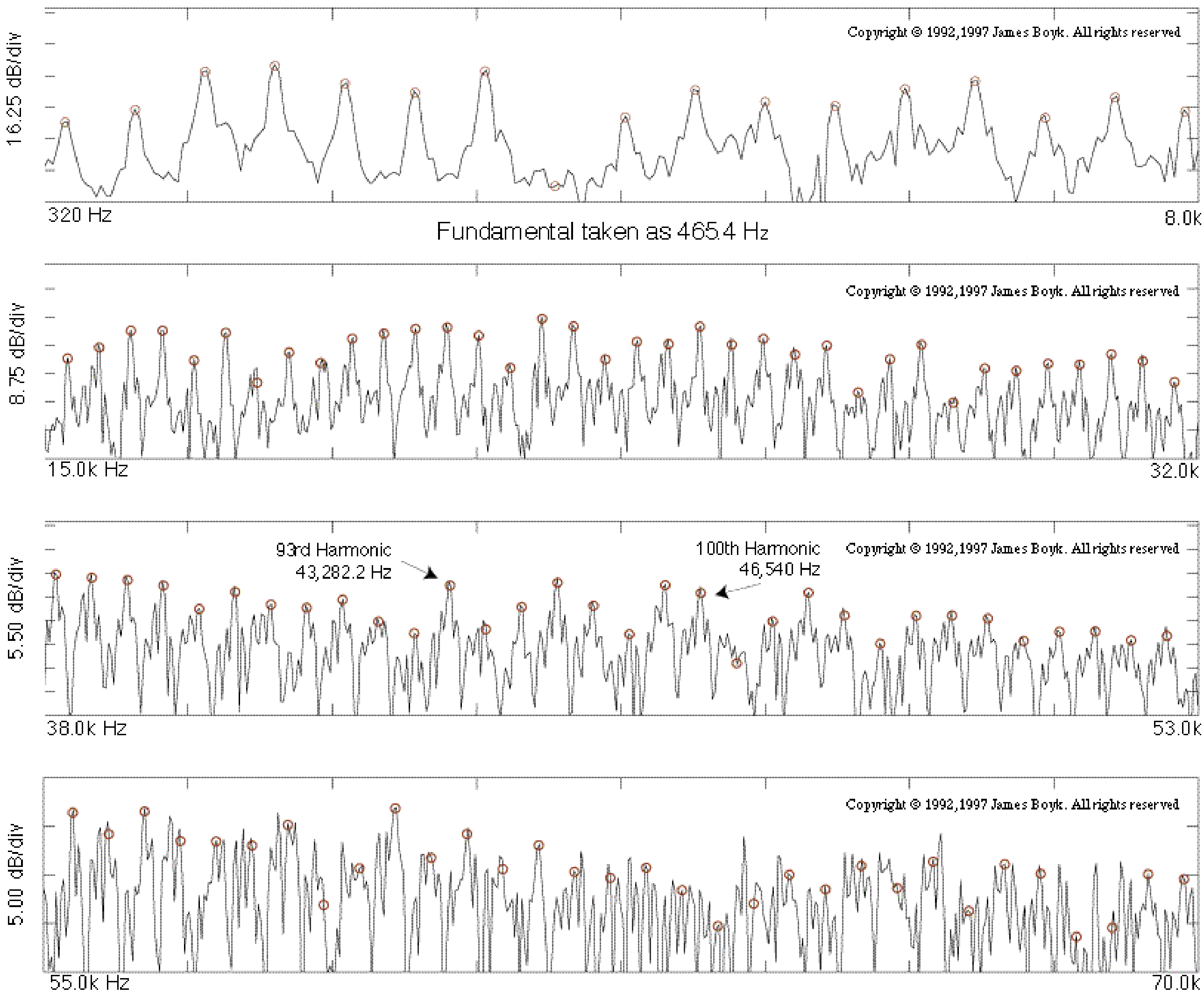

Figure 1(b) (Amplitude *vs* frequency). **Trumpet with Harmon mute**. Excerpts from the upper trace of Figure 1(a), to show more clearly the presence or absence of harmonics. Circles are placed at multiples (*i.e.*, harmonics) of the fundamental frequency. The dB scale has been adjusted independently in each strip.

II. Explanation of trumpet spectra in Figures 1(a) & 1(b)

The upper trace in Figure 1(a) shows the spectrum of a concert B-flat played on a trumpet with a Harmon ("wah-wah") mute, as captured by an Aco/Pacific quarter-inch microphone four feet away and analyzed with a Hewlett-Packard model 3567A FFT spectrum analyzer. This and all other instruments were played in normal concert fashion. (For details of instruments and players, see Appendix A.)

The lower trace shows the background with the trumpet silent; this is dominated by the microphone's "self-noise," as shown in section VIII, below. Of course this background is present when the trumpet plays; and that is why the upper trace is identified as "Trumpet + Background."

Are the trumpet peaks actually harmonics? To find out, we'd like to place markers at harmonic frequencies. To be easily readable, though, such a graph would have to be huge, so Figure 1(b) provides excerpts from it.

The first excerpt shows the spectrum up to 8 kHz; the second, from 15 to 32 kHz; the third, from 38 to 53 kHz. Note the 100th harmonic at 46,560 Hz and the 108th at 50,263 Hz. (The vertical scale has been adjusted separately in each excerpt to make it easier to judge the presence or absence of harmonics. Figure 1(a) shows the overall relationships of level.) It is clear that the peaks are indeed harmonics (and equally clear in the omitted portions of the frequency spectrum, for this and the other spectra).

The fourth excerpt shows that by 55 kHz, the harmonics are vanishing. Note that, as seen in Figure 1(a), the trumpet is still 12 to 15 dB above the background at this frequency; so the energy seen at 55 kHz, though non-harmonic, is still trumpet sound. To be conservative, however, I don't claim this portion of the spectrum as part of the sound; and Table I says only that harmonics are visible to "above 50 kHz." Similarly, where the last column in Table I shows that 0.5% of the total energy is above 20 kHz; this is calculated only to the 50 kHz limit given for the harmonics.

In Figures 2(b) through 9(b), as in this one, the last excerpt will show the region where visible harmonics vanish.

III. More trumpet, horn, violin, and oboe

In the same way as just described for Figure 1, Figures 2 through 9 give information about other instruments whose sound has harmonics.

Skipping Figure 1(c) for the moment, in Figure 2 we see another sample of trumpet with Harmon mute, 20 dB lower in level than the sample in Figure 1, yet with harmonics extending higher, and with a higher percentage of its total energy in the harmonics. (See Table I.)

Figure 3 shows trumpet with straight mute. Here the harmonics extend higher yet, to above 85 kHz.

Figures 4, 5, and 6 give three examples of French horn, played respectively "bell up," with mute, and in normal fashion. One hundred or more harmonics are visible in each!

Figure 7 shows a violin "double-stop", that is, two notes played simultaneously. Since each note produces its own harmonic series, Figure 7(b) uses markers of two different shapes to show the two harmonic series.

Figure 8 shows a single violin note played *sul ponticello*, that is, with the bow very close to the bridge. This gives a distinctive squeaky-scratchy sound which composers sometimes specify, as for example Beethoven in the C-sharp Minor string quarter, Opus 131. Even in this *mezzo-piano* (medium-soft) note, harmonics are still visible past 40 kHz. (Due to absence of mind, I took no sample of normal violin sound playing a single note normally.)

Figure 9 shows an oboe note. It is striking how the harmonics suddenly drop in level after the 40th at 43 kHz.

Not shown are any clarinet or vibraphone samples, because, as mentioned above, I could find no harmonic activity above 20 kHz anywhere in several samples of each, despite the closest "prospecting" with spectrum analyzer. These were the only instruments of the group that did not show such activity.

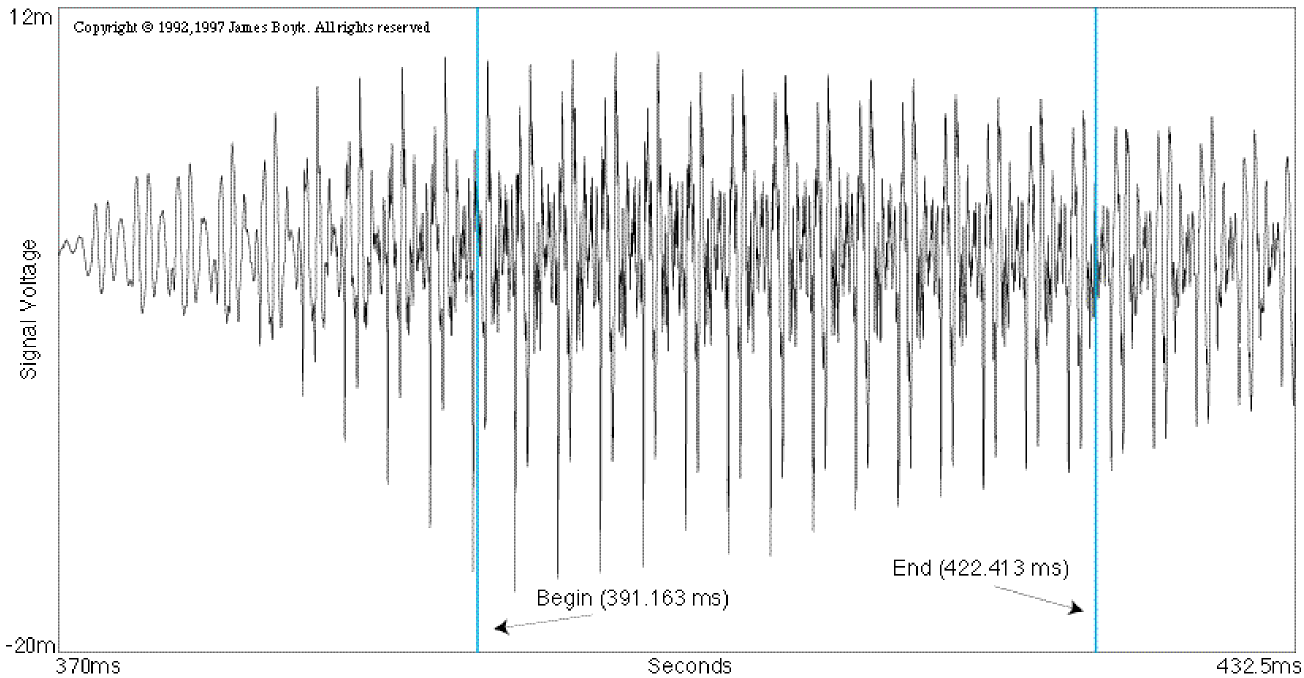

Figure 1(c) (Amplitude vs time). **Trumptet with harmon mute**. The time sample analyzed to make Figure 1(a). The trace shows, between the "Begin" and "End" marks, the 31.25-millisecond record from which the spectrum was created by Fourier analysis.

IV. Microphone and analyzer distortion

We return now to Figure 1 to ask whether the harmonics are spurious. Are they perhaps caused by overload of the microphone or analyzer? The waveform from which the spectrum was derived is shown in Figure 1(c), between the "Begin" and "End" points. Gross microphone overload would be shown by "flat-topping," which is absent. Nor was the analyzer overloaded on this or other samples. [1]

Microphone distortion short of gross overload is not a factor, either, according to information supplied by the makers of the microphones. [2] Capsule distortion is primarily 2nd harmonic, and falls 20 dB with every 20 dB drop in level down to 136 dB SPL (23 dB higher than any of my samples), continuing to fall below that level.

Since distortion is predominantly second harmonic [2], a spectral peak at 50 kHz, if due to distortion, would be the second harmonic of 25 kHz. If the 50 kHz peak were found to be at the 0.1% level, that is, 60 dB below the 25 kHz peak, then it might be due to distortion—if the distortion were indeed as high as 0.1%.

But in fact, the 50 kHz region in Figure 1(a) is 25 dB higher than this. Coupling this with the undoubted fact that the distortion is lower than 0.1%, the energy seen in the 50 kHz region is certainly not due to microphone distortion.

Similar reasoning applied to Figures 2 through 9 leads to the conclusion that microphone distortion is not a factor in any of them, nor by extension in Figures 10-16. However, in addition to such reasoning, I wished to test the microphones directly. Verifying the performance of the capsules (the diaphragm assemblies) is beyond the capability of my equipment; however, these units are widely regarded as a "gold standard" and their performance claims universally accepted as true. I rely on this.

I was able to test the preamps, however. I injected test signals into them via a B&K adapter, with a small capacitance to mimic the presence of the microphone capsule. Test signals were the following:

a. B&K 2639: preamp: A pure tone at 550 Hz, at a level 1 dB higher than that of the loudest musical-instrument sample.
b. B&K 2639: The same, but 1 dB lower than the softest musical sample.

c. B&K 2639 and Aco 4012 preamps: Tone cluster at 500, 1000 and 1500 Hz, 1 dB higher than the loudest musical sample.
d. B&K 2639 and Aco 4012 preamps: The same cluster, 1 dB lower than the softest musical sample.

Figures 18(a) and (b) show the performance of the B&K preamp to signals (c) and (d) respectively. The preamp is clearly free of harmonics at both high and low levels. The small bump at 85 kHz in the low-level test is breakthrough from the switching power supply. [3] I don't know the source of the even smaller bump at 50 kHz. Both are so small that they may be ignored, however.

The behavior of the Aco 4012 preamp was indistinguishable from the B&K 2639 at the higher level, and superior at the lower.

Note that these tests of the preamps are also tests of the H-P 3567A FFT analyzer. From the clean results, one may conclude that neither preamps nor analyzer are creating a false appearance in any of the spectra in this paper.

V. Room acoustics and rattles

I assume that the room acoustics are linear, and thus cannot create spurious frequencies in the spectrum. On the other hand, the room does contain objects which could conceivably rattle at ultrasonic frequencies, including loudspeakers, vacuum tubes, fluorescent light fixtures, metal chassis, and so on. What is more, the time samples analyzed for instruments with harmonics were generally long enough (31.25 milliseconds) for the microphone to pick up not only the direct sound of the instrument but also many reflections, and conceivably rattles, from around the room. (This is another reason that I do not claim greater high-frequency extension for these spectra than validated by visible harmonics.)

It is impossible however that these hypothetical rattles would fall precisely at frequencies that were harmonics for all the variety of fundamental pitches shown in the various Figures, so I discount rattles as a source of spurious harmonics.

VI. Instruments without harmonics

For sounds with no harmonics, the argument just given cannot eliminate the possibility of room contamination; so instead I attempted to eliminate the room from the sound. To do this, I analyzed only the very beginning of a sound (so the room was not already excited), and cut short the time record before the first reflection could return from the nearest surface. A shorter time record means coarser resolution of frequency; but since we're no longer looking for harmonic peaks, this does not matter. This procedure was followed for Figures 11 through 16; but first I present Figure 10, in which the speech sibilant of interest happened to come after the beginning of the sound, so any rattles might already have been excited. I believe Figure 10 to be all right nonetheless, for two reasons. First, the microphone was much closer to the desired source than to any possible rattle except those in the microphone mount, boom, or cable. Second, the spectrum presents a coherent picture. One would expect rattles to be at one or a few specific frequencies or narrow frequency bands; but this spectrum smoothly covers a very broad band. I rely on the latter point also to support my ignoring the possibility of rattles from the microphone cable, shock mount and boom in Figures 10-16.

In Figure 10, since the room was already excited by the sound preceding the analyzed segment, there was no point in limiting the length of the time record; so I used a 31.25-millisecond record for a high-resolution analysis of 32 Hz per spectral line. I hoped this might reveal rattles more clearly; but none showed up. In Figures 11-16, as described, I analyzed the beginning of the sounds and cut off the time records before the first reflections.

Figure 11(a) shows the spectrum of a claves strike; 11(b) shows the 60-microsecond rise from a standing start to 104 dB. If one discounts the first tiny wiggle, the rise takes just 30 microseconds.

Figures 12(a) and (b) show a jazz-style rimshot on a remarkably beautiful-sounding drum. (See Appendix A for identification of instruments and musicians.)

Figure 13 shows crash cymbals. Note that the energy at 20, 30 and 40 kHz is higher than at 2, 3 and 4 kHz respectively; and that at 100 kHz it is still far above the background. I had never heard crash cymbals up close before, but I now think that this sound would be adequate for a sound-track of either the Big Bang or the Apocalypse!

Figure 14 shows a strike of a ten-inch triangle.

Figure 15 shows keys jangling. Recording engineers often use this sound to test their equipment, and one can see that it is indeed demanding, with the energy at an elevated level from 7 kHz to above 40 kHz.

Figure 16 shows a high note on the piano (G-sharp 72, where the notes are numbered 1 to 88 from lowest to highest). I took the hardwood floor of the concert room as part of the instrument, since a piano is always on a floor; so I cut off the time-capture not before the floor reflection but before the reflection from the nearest wall, 12 feet away. Note that the partials are not harmonic, as one sees clearly in 16(b). I'm not sure how to divide responsibility for this inharmonicity between the strings and the soundboard, both of which can vibrate non-harmonically (the former acting as a 'bar' rather than an ideal vibrating string; the latter, because the solutions for a two-dimensional system, as the soundboard essentially is, are inherently non-harmonic).

Whatever the cause, even at middle C on the piano (not shown), the first seven partials do look harmonic; but higher partials of middle C do go increasingly sharp, and the 17th partial is where the 18th harmonic would be. (The way this non-harmonicity functions in piano sound, and perhaps in the meaning of piano music, might make an interesting study.)

VII. Aliasing and "window splatter"

Returning to the topic of possible errors in the spectra, note that a spectrum may be corrupted in more subtle ways than those already mentioned. Aliasing, for example, is the spurious appearance below the Nyquist frequency of energy actually above that frequency.

In the case of the H-P 3567A spectrum analyzer, the Nyquist frequency is 131,072 Hz; that is, the analyzer samples 262,144 times per second. Of course the analyzer has an 'anti-alias' filter, which eliminates aliasing as a problem. But it's interesting to note that, since my point is the mere existence of ultrasonic energy from musical instruments, aliasing would be no problem even in the absence of the filter; for the presence of aliased energy would mean that the musical instrument sound extends above 131 kHz, which would make my point even more strongly.

Besides aliasing, I also considered "window splatter." The phenomenon by which a pure sine wave appears in Fourier analysis not as a single narrow spectral line but broadened and with bumps decreasing in level on either side—this is well-known. Extending the idea, one can imagine that even if a spectrum had no content above 20 kHz, it might nevertheless *look* as though it did because of the adding-up of "bumps" from energy below 20 kHz. I call this putative phenomenon "window-splatter." (More generally, window-splatter means that every point of the spectrum is potentially affected by every other point; but we are concerned here only with the issue of energy above 20 kHz.)

To calculate the effect of window-splatter, we should construct an artificial spectrum that is flat up to 20 kHz, then convolve this truncated spectrum with the Fourier Transform of the Hann window. The result will be a spectrum whose energy above 20 kHz will be due entirely to window-splatter.

Luckily, it turns out that window-splatter is an insignificant source of corruption for this work. (Not non-existent, but insignificant.) Using the "Math" function of the H-P 3567A analyzer, I created a spectrum whose value was 1 at all points up to just short of 20 kHz. At 20 kHz and above, the value was 0. After the convolution, the point at 20 kHz was indeed raised to -12 dB relative to the constant spectrum, but points at higher frequencies were at -150 dB, indistinguishable from the computation noise. (Figure 17.)

VIII. Correcting for the microphones' response curves

With regard for the points already discussed — microphone and input overload, microphone distortion, room acoustics and rattles, aliasing and "window-splatter" — I see no reason to doubt the existence of the ultrasonic energy. I did however correct the figures to allow for the unflatness of the microphones' responses.

Each microphone has not one but a family of responses: on-axis or random-incidence, each with protective grid on or off. The on-axis response with the grid off is very flat to 100 kHz; with grid on, it is not flat, nor even known beyond 70 kHz. The random-incidence response is not flat with grid on or off; and the two curves differ.

I first considered how to correct the background spectra (the lower curve in Figure 1(a), for example). I reflected that if the microphone had no "self-noise," then the background I measured would consist only of ambient sound in the room. Since this comes from all angles in a random fashion (as verified in measurements not shown), and is therefore captured according to the microphone's random-incidence response curve, the correct spectrum would be obtained by applying the opposite of that curve to the measured background. In other words, if the random-incidence response curve supplied by the manufacturer is *down* by 5 decibels at a certain frequency, I should *raise* the background spectrum by 5 dB at that frequency to get a correct reading.

If on the other hand the room were silent, so that the measured background came entirely from microphone self-noise, then no correction would be necessary, since self-noise is generated electrically in the microphone, and has nothing to do with the presence or absence of the grid, nor with the angle of a source relative to the microphone.

Since the room is quiet and the microphone, like any quarter-inch microphone, is noisy, I thought it likely that microphone noise dominated. To check this, I compared two background measurements taken with the quarter-inch B&K 4135 microphone, one measurement with grid on and the other with grid off. These two spectra were identical; they superimposed even when viewed using a vertical scale of only 0.6 dB per division.

If I assumed that the background were dominated by room sound, I would "correct" each trace to allow for the unflatness of its particular microphone frequency response. The grid-on and grid-off random-incidence responses of the B&K 4135 differ by 3 dB at 30 kHz, 4 dB at 40 kHz, 1½ dB at 50 kHz and presumably by substantial amounts at higher frequencies, where the calibration of one of the curves is not known (that is, not supplied by the manufacturer).

Since the background spectra I obtained are identical, "correcting" them based on two different curves would give different spectra for the same acoustic background. This nonsensical result implies that the assumption was wrong and the measured background is indeed dominated by microphone self-noise.

I conclude that microphone self-noise indeed dominates the background measurements, and therefore that they are good over the full band without correction.

Now I consider the musical instrument spectra; for example, the upper trace in Figure 1(a). Here I take the applicable curve to be the on-axis microphone response, since the microphones were always pointed at the instruments. While the on-axis "grid-off" curve is very flat to 100 kHz, the "grid-on" curve deviates by as much as 6 dB, and moreover is not known beyond 70 kHz. When correcting the response of a "grid-on" measurement, I freeze the correction at the 70 kHz level; that is, I make it constant from 70 kHz on up.

It is likely that the grid-on response continues to roll off beyond 70 kHz, and that therefore a true correction would not freeze at 70 kHz but would continue increasing. This would raise the apparent level of the high-frequency energy. Thus, by freezing the correction, I am taking a conservative approach.

It is even possible, contrary to my assumption of two paragraphs ago, that the on-axis curves may not be the appropriate ones to use at all. At very high frequencies, because of the shortness of the wavelengths and the acoustic "liveness" of the room, the instrument may be picked up more in a random-incidence fashion. If this be the case, then because the random-incidence response is down 9½ dB at 70 kHz, I should raise the measured spectrum by 9½ dB at that frequency, and by appropriate amounts at other frequencies.

Thus, at very high frequencies the true spectra may be 10 or even 20 dB higher than the curves shown here. As I do not have facilities to decide in which fashion the microphone is picking up the instruments, I use the on-axis curves to be conservative.

Using the "Math" facility of the H-P 3567A analyzer, all the spectra have been corrected as described here, to within ±0.5 dB.

Table I. Ultrasonic Extension and Energy of Some Musical Instruments

A summary of this paper's findings. Column one refers to the figure showing the spectrum in question. Column two identifies the instrument. Column three gives the sound pressure level measured at the microphone. Column four gives the measured frequency extension: For instruments with harmonics, this is the highest frequency where harmonics are still present; for those without harmonics, the highest frequency where the sound is still at least 10 dB above the background. (See text.) The last column tells what percentage of the total energy is contained in the range between 20 kHz and the limit given in the previous column.

Instruments With Harmonics

Fig.	Instrument	SPL (dB)	Harmonics Visible To What Freq.?	Percentage of Power Above 20 kHz
1.	Trumpet (Harmon mute)	96.	>50 kHz	0.5
2.	Trumpet (Harmon mute)	76.	>80 "	2.
3.	Trumpet (straight mute)	83.	>85 "	0.7
4.	French horn (bell up)	113.	>90 "	0.03
5.	French horn (mute)	99.	>65 "	0.05
6.	French horn	105.	>55 "	0.1
7.	Violin (double-stop)	87.	>50 "	0.04
8.	Violin (*sul ponticello*)	77.	>35 "	0.02
9.	Oboe	84.	>40 "	0.01

Instruments Without Harmonics

Fig.	Instrument	SPL (dB)	10 dB Above Bkgnd. to What Freq.?	Percentage of Power Above 20 kHz
10.	Speech Sibilant	72.	>40 kHz	1.7
11.	Claves	104.	>102 "	3.8
12.	Rimshot	73.	>90 "	6.
13.	Crash Cymbal	108.	>102 "	40.
14.	Triangle	96.	>90 "	1.
15.	Keys jangling	71.	>60 "	68.
16.	Piano	111.	>70 "	0.02

IX. Results

Table I summarizes the results. Instruments with harmonics (Figures 1 to 9) are claimed to have energy to the highest frequencies where harmonics are still visible. Those without harmonics (Figures 10 to 16) are claimed to have energy to the frequency where they are still 10 dB above the background. These frequencies are listed in the fourth column of the table, while the last column tells what percentage of the total energy of each sample lies below these frequencies but above 20 kHz. That is, a figure of 0.5 in the last column means that half of one percent of the energy is above 20 kHz. As described above, every step has been taken to make these figures conservative, and the real figures may well be substantially higher.

For the samples which include room reflections (Figures 1 to 10), I do not claim that our spectra are the "absolute" spectra that would be found in anechoic measurement, because the spectra may have been altered by room resonances. As my point is simply the existence of the ultrasonic energy, however, this does not matter.

Since Figures 11 to 16 exclude room reflections, their spectra should indeed be quantitatively accurate to within the few-decibel total error of the analysis chain.

X. Significance of the results

Given the existence of musical-instrument energy above 20 kilohertz, it is natural to ask whether the energy matters to human perception or music recording. The common view is that energy above 20 kHz does not matter, but AES preprint 3207 by Oohashi et al. claims that reproduced sound above 26 kHz "induces activation of alpha-EEG (electroencephalogram) rhythms that persist in the absence of high frequency stimulation, and can affect perception of sound quality." [4]

Oohashi and his colleagues recorded gamelan to a bandwidth of 60 kHz, and played back the recording to listeners through a speaker system with an extra tweeter for the range above 26 kHz. This tweeter was driven by its own amplifier, and the 26 kHz electronic crossover before the amplifier used steep filters. The experimenters found that the listeners' EEGs and their subjective ratings of the sound quality were affected by whether this "ultra-tweeter" was on or off, *even though the listeners explicitly denied that the reproduced sound was affected by the ultra-tweeter, and also denied, when presented with the ultrasonics alone, that any sound at all was being played.*

From the fact that changes in subjects' EEGs "persist in the absence of high frequency stimulation," Oohashi and his colleagues infer that in audio comparisons, a substantial silent period is required between successive samples to avoid the second evaluation's being corrupted by "hangover" of reaction to the first.

The preprint gives photos of EEG results for only three of sixteen subjects. I hope that more will be published.

In a paper published in Science, Lenhardt et al. report that "bone-conducted ultrasonic hearing has been found capable of supporting frequency discrimination and speech detection in normal, older hearing-impaired, and profoundly deaf human subjects." [5] They speculate that the *saccule* may be involved, this being "an otolithic organ that responds to acceleration and gravity and may be responsible for transduction of sound after destruction of the cochlea," and they further point out that the saccule has neural cross-connections with the cochlea. [6]

Even if we assume that air-conducted ultrasound does not affect direct perception of live sound, it might still affect us indirectly through interfering with the recording process. Every recording engineer knows that speech sibilants (Figure 10), jangling key rings (Figure 15), and muted trumpets (Figures 1 to 3) can expose problems in recording equipment. If the problems come from energy below 20 kHz, then the recording engineer simply needs better equipment. But if the problems prove to come from the energy beyond 20 kHz, then what's needed is either filtering, which is difficult to carry out without sonically harmful side effects; or wider bandwidth in the entire recording chain, including the storage medium; or a combination of the two.

On the other hand, if the assumption of the previous paragraph be wrong — if it is determined that sound components beyond 20 kHz *do* matter to human musical perception and pleasure — then for highest fidelity, the option of filtering would have to be rejected, and recording chains and storage media of wider bandwidth would be needed.

XI. What Next?

A natural next step would be to measure the ultrasonic content of orchestral sound as heard from normal listening or recording distances. This will automatically allow for the absorption of ultrasonics by the air. The project will be expensive, because musicians' union rules require players to be paid at recording rates, which are several times ordinary "scale," whenever a live microphone is present; and I anticipate difficulty in having these rules waived for our research. We solicit funding for this project!

Acknowledgements

This project went from a long-held idea of mine to reality because of the enthusiasm of Scott Kelly, Sandee Perez and Hovel Babikian, students in my Caltech course "Projects in Music & Science," EE/Mu 107. I am grateful for their substantial help in getting started.

Without the help of my friend Prof. Gerald Jay Sussman of MIT, the work would not have been finished. As a visiting faculty member at Caltech during 1991-92, and continuing since then, he has contributed his deep knowledge, lucid teaching, and experienced counsel.

Sincere gratitude also to:

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the late Bart Locanthi, who was generous with his interest and knowledge;

Julie Sussman, for careful reading and useful comments;

and Daniel W. Martin, editor-in-chief of the Journal of the Acoustical Society of America; Patricia M. Macdonald, executive editor of the Audio Engineering Society Journal; and the anonymous AES reviewers; for their generous assistance and good suggestions. (This does not imply endorsement of this paper by these individuals or by their organizations or publications.)

This paper is being published long after the work was completed because of the difficulty of creating publication-quality graphs from the data. I spent a lot of time and money discovering half a dozen programs that would not make acceptable graphs. Finally, Caltech undergrad Peter Oakley learned to use Matlab to do the job, and carried out the work reliably and creatively.

The Web (HTML) programming of this paper was done by David Boyk, of MegaHard Design.

Appendix A. Musicians and Instruments

Measurements of all instruments except piano were carried out in the Music Lab at California Institute of Technology; piano was measured in Dabney Lounge, Caltech's superb small concert room. Musicians were asked to play as in performance, and to avoid artificial effects.

Figures 1 to 3. Trumpeter William Bing, Director of the Wind Ensemble and Jazz Band at California Institute of Technology, playing a Yamaha YTR 6335H trumpet with 135H lead pipe, YLH bell, and Yamaha 17D4 mouthpiece with Malone back bore. Mutes: EMO Harmon mute, stem in, played "straight out" (that is, uncovered); Dennis Wick straight mute.

Figures 4 to 6. Hornist Jeff Greif playing Conn 8D French horn. Mute: Humes & Berg, stone-lined. Though an amateur, Dr. Greif is an excellent and experienced player.

Figures 7 and 8. Violinist Linda Rose playing a Nicolas Gagliano violin, ca. 1782. Sartory bow, tourte mute.

Figure 9. Oboe student Katja Pelzer playing a Loree oboe with "mix & match" sections.

Figure 10. Caltech graduate student Paul Sivilotti speaking.

Figure 11. James Boyk playing an inexpensive claves of unknown origin.

Figures 12 to 14. Percussionist David Johnson playing, in Figure 12, a jazz-style rimshot on a Ludwig Super-Sensitive maple-shell snare drum from the 1920's; in Figure 13, a pair of Sabian 19-inch Germanic crash cymbals; and in Figure 14, a Grover 10-inch triangle using a Stoessel beater.

Figure 15. Professor F. Brock Fuller jangling his own ring of keys.

Figure 16. The author, who is Pianist in Residence at California Institute of Technology, playing Steinway Concert Grand CD 25 in Dabney Lounge at Caltech. The piano had just been tuned by concert tuner and former Steinway Concert Technician Kenyon Brown.

Appendix B. Measurement Equipment

A Hewlett Packard 3567A FFT analyzer, which captures 262,144 samples per second and has a dynamic range of 150 dB and a signal-to-noise ratio of over 80 dB, was used with two quarter-inch microphones, one a Bruel & Kjaer 4135 with 2639 preamp and 2807 power supply. the other an Aco/Pacific model 7016 with 4012 preamp and PS9200 supply. A half-inch Aco/Pacific 7012 was used for collateral measurements.

References

[1] Personal communications from Mac MacDonald and Steven Bye, Hewlett Packard: Overload in one portion of a time capture does not corrupt analysis of other segments. (The H-P 3567A analyzer shows overload by an "OVLD" legend on the time trace and by changing the overloaded portion to red; so it is very easy to tell whether any given segment is usable or not. A few of my captures had tiny overloaded segments, but I did not use these for analysis.) [back]

[2] Personal communications from:

Noland Lewis of Aco/Pacific: The specifications of the Aco 7016/4012 (mike/preamp) are the same as Bruel & Kjaer 4135/2639.

Erling Frederiksen of Bruel & Kjaer: Distortion of the B&K 2639 preamp is negligible at any level found in this work. Distortion of the B&K 4135 microphone capsule is predominantly second harmonic with magnitude 0.1% at 136 dB SPL. Falling by a factor of ten for each 20 dB of level reduction down to 136 dB, the distortion continues to fall at lower levels. [back]

[3] Personal communication from Joe Chou of B&K. [back]

[4] Tsutomi Oohashi, Emi Nishina, Norie Kawai, Yoshitaka Fuwamoto, Hiroshi Imai, High-Frequency Sound Above the Audible Range Affects Brain Electric Activity and Sound Perception. Audio Engineering Society preprint No. 3207 (91st convention, New York City). Abstract, page 2. [back]

[5] Martin L. Lenhardt, Ruth Skellett, Peter Wang, Alex M. Clarke, Human Ultrasonic Speech Perception. Science, Vol. 253, 5 July 1991, pp. 82-85. Abstract, p. 82. [back]

[6] Ibid., p. 84, last paragraph of main text. [back]

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