A Comparative Study of Power Spectra and Vowels in Guarneri Violins and Operatic Singing

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Abstract—This paper is the first of a planned series aiming to characterize what could be viewed as standards of excellence in the tone quality of violins played note for note by a world-class player. Here we begin with the most outstanding item in our data bank, the analysis of the Guarneri del Gesù "ex-Sauret", played by its owner Itzhak Perlman in a 2-octave chromatic scale. The second violin analyzed was the del Gesù "ex-Ole Bull". The tone quality of these violins is discussed in terms of their power spectra and similarities with those of the female singing voice. We have used a method of speech analysis, LPC with Praat, to determine the formants of vowels sung by a Metropolitan Opera soprano and those of the two violins. All the low notes of the voice and violins were then placed in a form of the IPA vowel diagram designed by Pfitzinger, whereby the vowels could be identified. Each violin has a characteristic distribution of vowels in the Pfitzinger plot, which can serve as identification and provide a basis for quality assessment. Some of the vowels are stable, others have a diphthong character. It appears that famous Cremonese instruments produce notes that gravitate toward certain type of vowels, implying that old masters could have used vowel identification as a means of quality assurance. We suggest that the user-friendly methods described here would be a useful supplement for makers and players in evaluating the quality of their own violins.

I. INTRODUCTION

Many current makers of fine violins rely on physical measurements to prove the high quality of their violins. The gold-standard of objective quality control is provided by frequency response curves which are obtained generally by two methods: tapping of the bridge [1, 2], or using electromechanical excitation of the bridge [3], and recording the sound emission by a microphone. The largest experiment of the latter kind was conducted by H. Dünnwald who analyzed some 700 violins, both old and new, and presented averaged response curves for various categories of violins. The two notable differences between the old Cremonese violins and the new master-violins were a stronger emission in what he called the nasal range, 900 to 1400 Hz, and also at the very high frequencies from 5000 to 9000 Hz in the latter group [3]. Jansson [4] and Buen [5], who measured the long-time average spectra of bowed violin music, provided additional information about the differences between groups of violins. Yet some established researchers concluded that there are no convincing physical measurements that would prove the superiority of the old Cremonese violins over the best new ones [6, 7]. To date, physical investigations have not gained popularity among musicians, who may consider them unsatisfying or not user-friendly. Perhaps objective methods are not refined enough to reveal small but significant differences among the finest violins. It is also noteworthy that a recent experiment in which blind-folded players compared violins made by Stradivari, Guarneri del Gesù and modern makers failed to prove the anticipated superiority of the antique violins [8].

Thus far, physicists seem to generally eschew the intuitive proposition that violin tone quality may be studied by focusing on the sound produced by a competent violinist, although many textbooks rely on power spectra of musical notes as a convenient means of characterizing the tone color, or timbre, of various musical instruments. Yet, there is a dearth of published research on the spectra of violin notes [9-14], and none of them represent a famous violin played by a world-class player. It was a welcome development that the first thorough examination of the individual violin notes has been undertaken by outsiders and newcomers, whose own expertise was in the area of speech analysis and neuroscience. The old notion that the violin can sing and its notes can resemble human vowels has become a current focus in the analysis of tone quality.

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The ground-breaking work on the vocality of individual violin tones was carried out only a few years ago in Hamburg, Germany, by Stella Müller, under the guidance of Professor Robert Mores. Her thesis, available in German only, is an excellent primer into the methods of speech analysis as it applies to the identification of vowels in the notes of violins [15]. R. Mores has also addressed himself to the issue of nasality in violins [16, 17], taking a position contrary to the prevailing view of H. Dünnwald [3]. A second insightful paper by Tai and Chung [18] was based on the recordings of the best violins from the Chi Mei Museum of Taiwan, which included some precious Cremona violins in addition to several fine violins of later periods. The main conclusion of the research was the discovery of significant gender-like differences between the groups of violins, the Stradivaris being the closest to female voices.

I began my investigations on the relationship of violin timbre and the human voice in the late 1980s when computer-based FFT spectrum analysis became available. At the outset I did not consider the results of speech analysis, the formants of the spoken words, to be applicable to the violin because energy emission declines very rapidly above the first formant. The speech vowels do not project well and they are short in duration in comparison with a bowed string instrument. Since much of the male voice falls below the lowest notes of the violin, the violin sound has clearly a female character. To me the violin often resembles the trained operatic voice, and hence I felt it necessary to gain the cooperation of a Metropolitan opera soprano and several young girls to assemble a library of vowels sung on a musical scale. A comparison of the spectra of a Strad and a del Gesù taken on the note A220 Hz and a tentative assignment of their vowel character was published in the now-defunct The Chemical Intelligencer in 1996 [19]; I also posted a brief essay on the vowel character of some violin notes on my website http://nagyvaryviolins.com/tonequality.html in 2002. This essay describes the discovery made in 1995 that the power spectrum of the vowel in the French word peu, sung by my then 10-year old daughter, was almost identical to the spectrum of the open D sound on one of my violins. This finding suggested that the issue of vocality in violins could be approached by a comparison of the respective power spectra.

Over the years since 1986 I have recorded power spectra of hundreds of modern violins and dozens of old Cremonese violins, and no two of them were identical for a variety of reasons. It is well known that the antique violins have experienced numerous alterations and intrusive repairs, which could be contributing factors for the great variation of their spectra. For this reason one has to be careful when making a generalized statement concerning all the works of any particular maker. Each violin should be judged individually by the evaluation of every note. Two bad notes can almost nullify the value of a violin for a soloist, something which is not so apparent when average values are compared. The comparison of spectra from the musical scales of the old Cremona violins and the singing of soprano singers has lead so far to a tentative description of what characteristics any particular note should ideally possess. My tentative conclusions in this regard will be a part of the Discussion section in this paper. Since the mass of spectra inherent in the establishment of such a comprehensive data library are impossible to present in one research publication, here I describe the results obtained on two superior violins of Guarneri del Gesù, which were highly prized by famous soloists, but are characterized by rather different structural and tonal features. Each of these violins exhibits certain spectral characteristics that come close to representing a possible standard of excellence, however personal and subjective such a value judgment might be. At the very least, the availability of these spectra would offer an opportunity to both players and makers to test their instruments note for note against some of the most famous Guarneri violins. We also analyzed the violin notes for their formant content using the linear predictive coding (LPC)/ Praat program posted on the internet by Paul Boersma [20], which has found widespread use in speech analysis. We also made use of the methodology pioneered by Mores and Muller [15-17] and Pfitzinger [21] to identify the specific vowels to which the low notes of the violins come the closest. Our findings on the vowel content of these violins seem to lend some support to the supposition that the Old Masters could have relied on vowel recognition as a means of establishing a certain identity and quality of their violins.

Although many physicists and engineers are interested in all matters pertaining to the tone quality of the violin, this article is also addressed to the multitude of violin makers and violinists who would be highly motivated to get in their hands a relatively simple method to assess the tone quality of their violins. To this effect, I describe a methodology that is relatively inexpensive to acquire and easy to learn. With the help of this methodology, we seek to answer the following questions of general interest. How can we characterize the singing quality of the individual violin notes? Are there any metrics or other features to describe what is desirable or undesirable in the tone of a violin as it is played note for note? To what degree can we determine that a note of the violin resembles a certain vowel of singing voice? What kind of vowels should a top quality violin possess? What are the features or metrics that can be used to assess the sonority and the projection of any note? This paper is the first of a projected series, beginning with Guarneri del Gesù, and to be followed by describing some outstanding violins of Stradivari, JB Guadagnini, Nicolaus Gagliano, furthermore some French and modern makers. The ultimate goal of this research is to pave the way to making the sound, instead of its label, the primary commodity of the violin.

It is important to acknowledge that the approach presented below is essentially a subjective one, and it is only aided by a modern method of signal analysis. We analyze sound samples that were recorded under a variety of conditions, giving rise to a number of independent variables. How we can deal with these variables and extract useful information for the sound will be explained below in the Methods.

II. Theoretical Background of the Experiments and Methods of Execution

A1. The relationship of power spectra and the frequency response function of violins

The complex physics of energy transfer from the bowed strings of the violin through the bridge to the body was studied by many authors; it was described in the simplest terms in a prize-winning popular presentation by Colin Gough [6]. The Helmholtz motion of the applied impulse introduces a saw-tooth force on the top of the bridge, which in turn forces the violin body to vibrate and radiate sound. Like the vibrating string, the emitted sound of the violin's body has rich harmonic content, a series of partials, but the latter has a much more complex waveform and spectrum. The amplitude of each partial in the audible sound is determined by the mechanical resonances of the body and the bridge at that particular frequency. Large amplitude is observed when the exciting frequency of a partial coincides with a vibrational mode of the violin. The bridge has a vital function not only in the transfer of energy from the strings; it also contributes two important radiating resonances, one somewhere between 2.5 and 3 kHz due to a rocking motion, and one around 4.5 kHz due to a vertical up and down motion.

The strong low frequency resonances of the violin have been studied by several authors, and they are present in all violins [22-24]. The first of these is the air resonance A0 which is often found between C# 277 Hz and D 294 Hz; it is significantly stronger in the Cremonese violins than in most 20th century violins [3]. Following a couple of weak resonances, one encounters the two strong body resonances deriving from the corpus bending modes B-1 and B+1. According to a survey of 47 fine old violins by A. Buen*, the average value and standard deviation for B-1 was 444 (15) Hz, and for B+1 537 (20) Hz. In the opinion of many makers, including mine, A0 and B+1 are believed to be the most important modes in controlling tone color, and they can differ significantly between violins [23-24]. The fine old violins have relatively low emissions between D 587 Hz and G 784 Hz, followed by minor peaks at B 988, F# 1480 and G 1568 Hz. Above this frequency commences the steady rise of the "bridge hill", an assembly of many close resonances, which have their origins in the bridge and its surrounding area of the belly between and near the two f-holes. The bridge hill declines somewhat above 3 kHz, but two more resonance hills follow which are centered around 3.5 kHz and 4.5 kHz; the latter one could be, as mentioned earlier, due to the bridge itself. There is also a considerable emission above 5 kHz, but this may have more significance to the playability of the violin than to the quality of the sound heard by the audience. Many modern violins have higher emission limits than the old Cremona violins, which may be a factor in perceived harshness of the sound.

The totality of these resonances, as they are depicted in the frequency-response curve, is the most fundamental attribute of a violin, like DNA is for living organisms; they give some idea of what the power spectrum of each note could be. However, knocking at the violin bridge can never be a substitute for playing it, if we want to appraise its tone quality [25]. It is impossible to draw an accurate power spectrum of a note on the basis of the frequency-response curve because we don't know the extent of coupling between neighboring resonances, and so much depends on the player's skill in placing emphasis on certain partials, either in enhancing them or repressing them.

A2. The uncertainties of working with recorded sound samples

The approach I have been following is a combination of objective instrumental analysis with several subjective components associated with how the sound was recorded. Once a recorded sound sample of a violin tone is available, its analysis via FFT based signal analyzers is a straightforward process, and the resulting spectra at the specified time frames would not depend on the person doing the analysis. Neither would there be much uncertainty in the assignment of vowels by the objective methods of speech analysis. However, there is a high degree of uncertainty concerning the manner the recording itself was carried out which needs to be evaluated and dealt with in order to obtain any useful sound samples.

The recording of violin notes involves a large number of independent variables, such as: the player, the acoustical environment, the microphone and its positioning, the choices of the bow, the strings, the chin-rest, the shoulder-rest, and the relative humidity. Of the variables listed above, the first two—the production of the sound by the player in a variety of acoustical environments—are the most critical ones. It has been my experience that the same violinist can

* A. Buen, private communication.

generate a variety of tone colors, i.e., power spectra, on the same note, even in the same bow-stroke, and that even more deviations in the spectra can be observed when two players play the same note on the same violin. Not every professional player is capable of good tone production and doing justice to a fine violin, which may also depend on bowing mechanics and acclimation to certain instruments. Concert halls vary a great deal in the quality of sound they deliver to various locations within them; and so do studios and living rooms. The situation appears hopeless unless certain conditions are met, which are the following.

In order to evaluate the violins based on their sound, it may be advantageous to have a violinist who is experienced in playing Strads and Guarneris and other top quality violins. The player should be allowed to get familiar with the particular violin to be tested, its dynamic range and responsiveness. The violin must be warmed up by playing every position of its entire range several times. Strong dynamics of forte to fortissimo should be employed with repetitions to bring out the maximum power of each partial, including the ones at high frequencies. In our experience when these conditions are met a qualified player can produce a sound with reasonable reproducibility; a sound that is characteristic of the particular violin. Keeping the same conditions, a second qualified player is also able to reproduce the sound with only minor deviation in the spectral envelope. There would be differences, but they would not significantly alter the vocality of the sound, which is our main concern.

The acoustics of the room is the second critical issue. Unfortunately, it proved to be impossible for me to coral the great violinists with their fine violins into an anechoic chamber, or the outdoors, the latter often being a satisfactory second-best choice. I had to do my recordings according to the circumstances in smaller rooms or recital halls. Of course, most makers and players would have no access to an anechoic chamber, and must do their measurements in their own home environment. Under those conditions, one has to deal with the vagaries of the acoustical environment that can lead to the enhancement or attenuation of certain partials; therefore the suitability of the testing room must first be established. For this purpose, I have always made prior tests on a well-known violin of my own in order to find the location where the familiar power spectra could be reproduced. The employment of two microphones, placed diagonally in the room at two distances also helped to find any abnormalities in the spectra. It should be emphasized that the recording done in different rooms is valid only when done at a close distance to the microphone. It is necessary to point out, as a factor in the acoustical environment, that the radiation of the sound from the violin has a marked directivity, which was studied in detail by Weinreich [26]. Therefore, the angle of the microphone above the plane of the violin must also be standardized. During the past 25 years I had the opportunity to analyze the sound of many violins both in our anechoic chamber and in a variety of rooms and halls. I have, more often than not, found locations within rooms at my disposal where the signature images of the individual notes of the familiar violin were similar, with the exception of one or two notes out of twenty five. A meaningful, however subjective, argument for the validity of such spectral measurements is the quite universal human experience that spoken and sung vowels do not change in any noticeable manner at a short distance to the listener, no matter where the location is. Thus, the vocality of violin notes is also not expected to change in any significant manner.

The reader should also be aware of the subjective bias that concerns the choice of only one spectrum representing each sound sample in this study. It would be more informative to provide for each bow-stroke a larger number of spectra, or a 3-D figure that includes the time, but both would be cumbersome and require a lot of space. I selected from each sound sample the time frame where the spectrum is relatively stable, and therefore most typical for its graphics and the determination of its vowel characteristics. Other operators might make a slightly different selection. The question still remains concerning the choice of the more valid spectrum in the rare instances when the two microphones deliver two strongly deviating spectra. I favored the one which was closer to the spectrum of other fine violins on the particular note since it is more likely for random external factors to create dissimilarity than similarity. Thus my bias of choice was informed by cumulative experience gained on many violins.

The other factors listed above play only a minor role in determining the vowel character of a sustained note. There will always be minor changes in the shape of the spectral envelope, but these would not exclude the possibility of arriving at a dominant vowel sensation. Encountering some ambiguities would not invalidate the bulk of vowel assignments.

B. The human voice as a model for violin sound

According to the scientific analysis of voice in speech and singing, which is summarized in standard textbooks of acoustics [27, 28], each vowel is characterized by a set of formants; a formant being a certain range of frequency with high acoustical energy emission. In the current scientific analysis of speech, generally four formants are used to identify a vowel, the first two being the most important. The numerical frequency values of these formants are extracted from the power spectra at a point of steady state by the algorithm of linear predictive coding (LPC) [29]. Since the power spectra of spoken vowels and those of the violin notes are very different in that the former ones have very low emissions above the first formants, one could not be sure a priori that the methods of speech analysis could be applied to violins. However, it was a reasonable assumption, and it has now received some experimental support through the work of researchers in Hamburg [15-17] and in Taiwan [18], both of whom settled on LPC as the most suitable option.

Frequent references to the speaking and singing quality of the violin suggest that several of its notes were sensed to possess some vowel-like characteristics. In a 90-year old study of this kind uncovered by H.C. Tai [30], children were found to be quite adept in recognizing three vowels in three notes of the violin. This is truly remarkable if we consider the differences of how the human voice and the sound of the violin are produced.

The vocal tract with its constituents the larynx and the vocal cord within the throat, the pharynx, the tongue, the teeth and the nose represent a biological marvel of phonation. The vibrations that generate a series of overtones are originated by the vocal folds, but the spectra of the formants is shaped to a great extent by a filtration mechanism of great plasticity, which operates by the following means: 1. by the movement of the mouth from almost closed to wide open, while also changing the shape of the opening from a rounded to a horizontally stretched one; and 2. by the movement of the tongue along the horizontal and vertical axes, from the front to the back, and from down to up. Well specified positions of the mouth and the tongue can produce the standardized sounds of the speech vowels, and are also capable of imitating many natural sounds. Each position within our vocal apparatus produces standing waves at certain frequencies due to the arising resonances. One of the remarkable attributes of human phonation is that we are able to sing all vowels on every note of our musical scale, although there is a loss of distinction in our second octave over C 526 Hz as the partials become more separated and less in number.

The sound generating mechanism of the violin is much more restricted by its rigidity, and it is superior only in the wider frequency range of its four strings, which can also provide a more secure pitch than the human voice. In contrast to the voice, the timbre of the violin tone is due to its greater variety of vibrating elements that are selectively brought into resonance with the appropriate vibrating modes of the violin string. The violin does not have any visibly moving filtration mechanism to shape the power spectra of the notes, although some of its parts could selectively absorb energy without radiating it. The special tone color of each violin note comes about mainly by the enhancement of certain string modes by the corresponding resonance modes of the belly; the radiation from the back and the ribs are of lesser significance. This mechanism makes it impossible for a violin to imitate more than one or, in some instances, two vowels at any given pitch. It is a marvel of construction that any note of the violin could emit a recognizable vowel at all.

The identification of the vowel content of any violin note-for-note is a worthwhile objective of current acoustical research because it might become a basis of comparison according to a measurable quantity which can also be connected to a subjective value judgment. It has remained a challenging task because the large changes in fundamental frequency inject a degree of uncertainty. In previous studies plotting the formants F2 versus F1, it was observed that the same vowels spoken by children, women and men are separated and scattered because of their respective ground-frequencies of speech, F0, which for children can be about twice as high as for men [31]. In absence of knowing and making corrections for the different F0 values, one cannot make reliable assignments for vowels in the F1-F2 plane [15]. Further complication of the problem is that F0 can vary according to the size of the vocal tract and all of its components, but it is also necessarily varied by the same source of musical sound, being identical to the pitch of the musical scale. A novel approach to include F0 in combination with F1 and F2 for a more accurate identification of vowels was published by Pfitzinger [21].

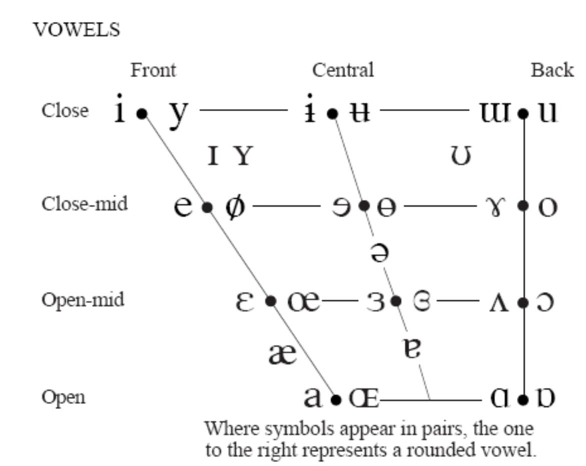

Figure 1 - The IPA Vowel Diagram. For the abbreviations and sound samples go to: http://www.phonetics.ucla.edu/course/chapter1/vowels.htm

Instead of using the F1-F2 coordinates, many phoneticians rely on the diagram that was first developed by Jones [32] for the cardinal vowels. This has the shape of a trapeze, in which the vertical direction represents the increasing height of the tongue position (some prefer to view it as the open or closed state of the mouth), and the horizontal direction represents the "backness" of the tongue, going on the Jones diagram from left to right as the tongue moves from the front to the back. In time, the Jones diagram has been extended by the International Phonetics Association

(IPA) to include the peculiar vowels of many foreign languages (**Figure 1**). The vowels of most languages can be assigned to specific locations in a trapezoid space which in the vertical direction represents the openness of the mouth and in the horizontal direction the position of the tongue from front to back.

In his ground-breaking work Pfitzinger [21] sought to establish a connection between the empirical and semi-quantitative positioning of vowels in the Jones-IPA diagram—which are not easy to measure—and the F0, F1 and F2 values of the individual vowels. He gave concrete values for the three vertical lines of the diagram in an x-y coordinate system, calling the x values backness, *b*, and the y values height, *h* (instead of openness). Any vowel can then be depicted, once the formant values were determined, by the following two empirically derived equations:

$$b = 1.782 * \ln(F1) - 8.617 * \ln(F2) + 58.29 \quad (1)$$

and

$$h = 3.122 * \ln(F0) - 8.841 * \ln(F1) + 44.16 \quad (2)$$

where ln() is the natural log function. Pfitzinger's template for the quantitative vowel assignment, which I have used in these experiments, is accessible on the Internet at:
http://www.citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.69.8327&rep=rep1&type=pdf

C. Recordings

The recording of the "ex-Sauret" Guarneri del Gesù (1743) took place in a dressing room of the concert hall in San Antonio in 1987, and it was played by its owner Itzhak Perlman. The violin was set up with Dominant strings; the bow was made by D. Peccate. Two B&K microphones were angled at the violin at 60 degrees from a distance of 0.9 m and 1.5 m. The sound was recorded by a Sony professional DAT tape recorder (sampling rate 44.1 kHz at 16 bits), and it was later saved on CD. Mr. Perlman played a 2-octave chromatic scale, each note twice with down-bow in dynamics of forte. The request for no vibrato was not followed strictly; some notes had a small narrow vibrato. The note A220 was also played in fortissimo with significant vibrato in the customary way Mr. Perlman would play in a performance. No shoulder-rest was used. Both the player and the violin were warmed up to the task, as Mr. Perlman was actively rehearsing for the performances on consecutive days. He also played notes on my standard violin under the same settings. Humidity was approx. 60%.

The recording of the "Ole Bull" Guarneri del Gesù (1744) was made in the Chi Mei Museum Auditorium in Taiwan by Dr. H.C. Tai whose paper [18] provides details of the recording conditions. We do not know how familiar the violinist, Agnes Feng, was with the instrument, and if it was properly warmed up. Like many violinists nowadays, she was using a shoulder-rest, which can change the balance of power in some notes—most noticeably at the two B resonances around A440 Hz and C526 Hz—between the strong fundamentals and the higher partials for the detriment of the latter. The high quality of the sound and the spectra suggest that the violinist was very competent. In addition to the Ole Bull, Dr. Tai has provided us with the recordings of 12 more violins, including one of mine (Nagyvary-Chen label); in each case a 3-octave G major scale was recorded. The recordings of these violins revealed no noticeable distortion of the sound under their recording arrangements. Humidity was near 50%.

The voice of Ms. Emily Pulley was first recorded in 1993, soon after she won first prize at the Metropolitan Opera national competition. The recording was done in the anechoic chamber built by Dr. Robert Kenefick, professor of physics, in the Biochemistry Field Laboratory at Texas A&M University. Only one B&K microphone was used with the DAT recorder. Ms. Pulley sang all six vowels of the Italian language in a G major scale starting at A220 Hz up to G 588 Hz. I did a second recording with Ms. Pulley in December 2011 in our private music room using a Zoom Q3 digital recorder with 2 condenser microphones in x-y configuration. This recording included three nasal vowels of the French language (en, in, un), the rounded front vowels that are common in several European languages, theő and ű (like the French peu and vue, the German Főhn and Műh'. In these vowels the lips form a small round opening like in whistling). She also gave us samples of the unique vowels in the English words bid, bad, and love. Unfortunately, the pitch in these recordings turned out to be low; corresponding to A 420 and 425 Hz, but this had no noticeable effect for the purpose of our analysis.

D. Power spectra

FFT spectra of all sound samples were analyzed by the SpectraLab analyzer from Sound Technologies. The program was set to a sampling rate 44100 Hz, FFT size 4096, time resolution 15.79 ms, spectral line resolution 10.77 Hz; Hamming window. A typical example of recorded sound of a partial scale in the time domain is shown in

Figure 2, which depicts the sound as amplitude vs. time for two renditions each of the notes G196, G#208, A220, A#233, B247, C263, and C#277 played by I. Perlman. The .wav file of each note of both violins can be found in the Sound Samples folder. The time scale of each note was expanded individually and analyzed from the beginning of the sound onward in 100 ms steps in order to find the most stable and typical region. Then an average spectrum was taken of an approx. 300 - 400 ms interval using the averaging option of SpectraLab. The same process was applied to the sound of both microphones, and the results were compared. The default negative dBV scale values in all spectra were converted to positive numbers by adding 100 to each in order to get our graphs into a positive, dB-like scale. These values might deviate from the actual sound pressure dB values, but this does not matter since the entire approach considers only the relative amplitudes of the peaks within each spectrum.

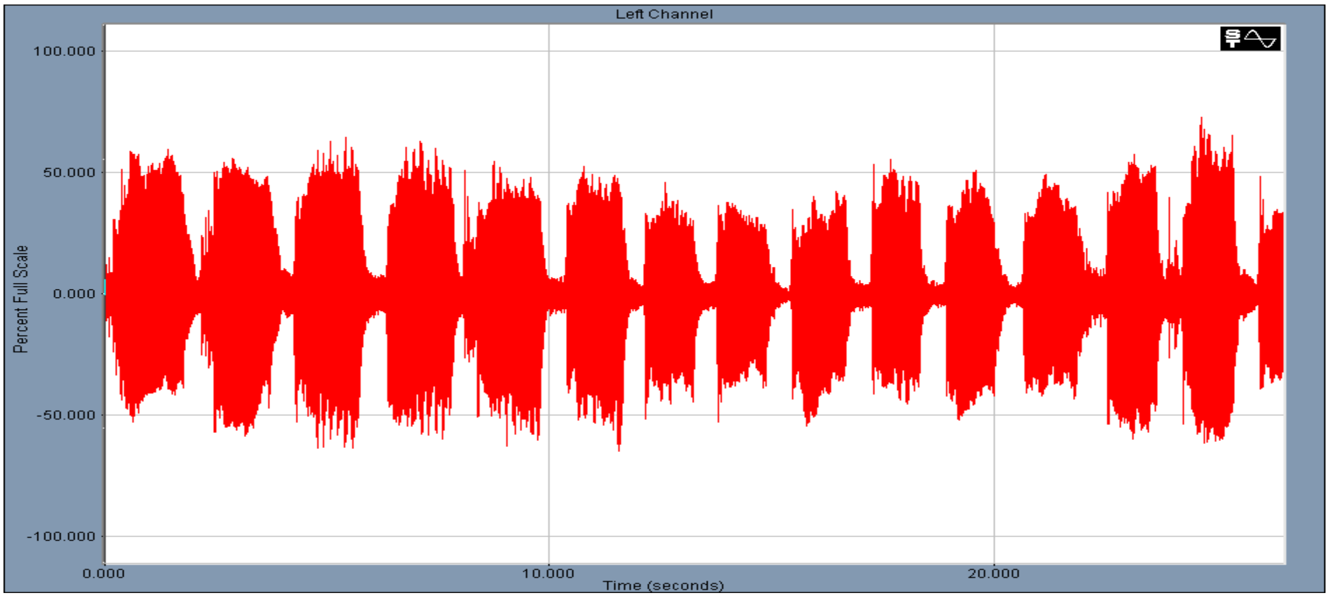

Figure 2 – The beginning of the chromatic scale on the "ex-Sauret" Guarneri played by Itzhak Perlman; partial recording of notes in the time domain of SpectraLab.

E. The extraction of vowels

I have been using the LPC analysis by Praat program (version 5.3.23) that was made available by Paul Boersma and David Weenink of the University of Amsterdam on the Internet site http://www.fon.hum.uva.nl/praat. The same program was used by Tai and Chung [18]. To put it in the simplest way, the Praat program takes the data of the FFT power spectrum and determines the center of each strong cluster of partials in the form of the LPC spectrum whose maxima represent the formants F1 through F4 or F5. A useful tutorial for the Praat program was written by P.van Lieshout of the University of Toronto [33]. The default settings of Praat had been adjusted for the purposes of speech analysis, and the applicability of those settings had to be examined in the case of violin sound analysis. Speech analysis requires pre-emphasis for the power of the higher formants which are otherwise too low. There was no need for any pre-emphasis for violins. For LPC spectra, it was mandatory to resample the wave files from 44100 Hz to 11025 Hz. I have also expanded the default time window from 0.025 to 0.05 and 0.15 s, the latter having been used by Tai and Chung [18]. On the advice of Dr. R. Mores [34], I have also compared the LPC spectra and formant values taken at the default prediction order 16 with the less sensitive order of 11. The sound samples from each microphone were analyzed separately for 4 formant values. The program allows for the inspection of the changes in formant frequencies with time.

Figure 3 shows the typical graphs we acquired for each note. It represents the analysis of the note G196 of the Sauret violin played by Perlman. The primary information is the FFT spectrum shown in black, which is the basis of the calculation by the LPC program. Superimposed are the LPC spectra taken at order 16 (red) and order 11 (blue). The latter effects a smoothening of the peaks and a small shift of the formant values. The formant traces vs. time are shown on the right side of **Figure 3**. The beginning and the end of a bow-stroke are always accompanied by rapid changes of spectral values, and therefore the relatively stable central portion was routinely used for analysis. The inspection of the LPC spectra gives us an idea about the relative strength of each formant. Weak formants represented by small and asymmetrical peaks or shoulders can be easily overlooked by our auditory senses [15]. The note G196 had a relatively stable formant pattern, but many other notes had shifty formants. For the construction of **Figures 8** and **12**, the formant values were obtained by using the same Praat parameters which were employed by Tai and Chung [18] (sampling rate 44.1 kHz and 0.15s time window). In this manner, I could compare my analyses of the violins with theirs, where the differences would be mainly due to the selection bias of what one considers the most representative time spot on the formants vs. time diagrams. I selected the most typical frequencies of F1 and F2 for the calculation of the *b*, backness, and *h*, height values according to the above mentioned Pfitzinger equations. These *b* and *h* values were then imported into the Pfitzinger plots.

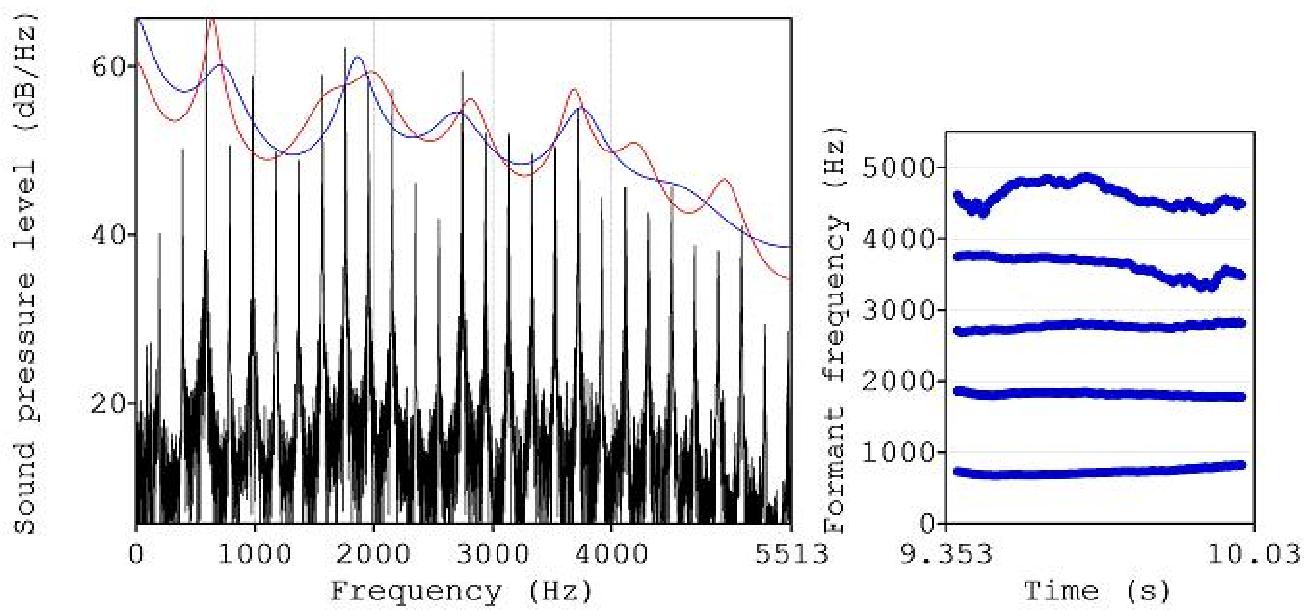

Figure 3 – An example of analysis by Praat applied to the note G196 of the "ex-Sauret" violin of Perlman. On the left: FFT power spectrum (black), LPC spectrum at order 16 (red), and order 11 (blue). On the right: the traces of 5 formants during 0.68 sec of the bow-stroke.

III. RESULTS

A. The power spectra of Italian, French, and English vowels sung by an operatic soprano

It has been a long-standing notion that the sound of the violin has a lot in common with the human voice, and it is often perceived as speaking and singing to the listeners. It seemed reasonable to compare the sound of violins with its closest human relative, the female soprano voice using the same system of analysis: the power spectra and the respective formants derived from the LPC spectra. The very active field of speech recognition analysis has generated numerous tables of formants for many vowels [34, 35] that one had to consider as an important reference basis for our violin quality studies. However, the sound of the spoken word had little appeal to me since it resembles short staccato sounds on a rather monotonous scale, and the spectral slices from spoken vowels do not at all resemble the spectra of violins. I was fortunate to have gained the collaboration of Ms. Emily Pulley in 1993 at the beginning of her career as a soloist with the New York Metropolitan Opera. Her voice at that time was typical of a young lyrical soprano voice which had both ample depth and considerable brilliance.

Our first recording with Ms. Pulley was done under ideal conditions in an anechoic chamber in the total absence of reverberations. What seems now a major omission, she was asked to sing only the 6 Italian vowels, which are considered cardinal vowels of all languages. Five of them are written in Italian as a, e, i, o, and u, which were designated by us (meaning my American students) as ah, eh, ee, oh, and uh; similar to the words bar, bear, beer, solo (spoken as monothong), and moos. The sixth Italian vowel is written as o, but it is pronounce like awe. (For example, Antonio.) All these vowels were recorded in at least eight notes of a G major scale starting with A 220 Hz. The most informative of these spectra are the ones taken at the lowest pitch, 220 Hz, which has the closest spaced and largest number of partials, thus most effectively mapping much of the important audio range. These spectra are shown in **Figure 4**, while others are available on request.

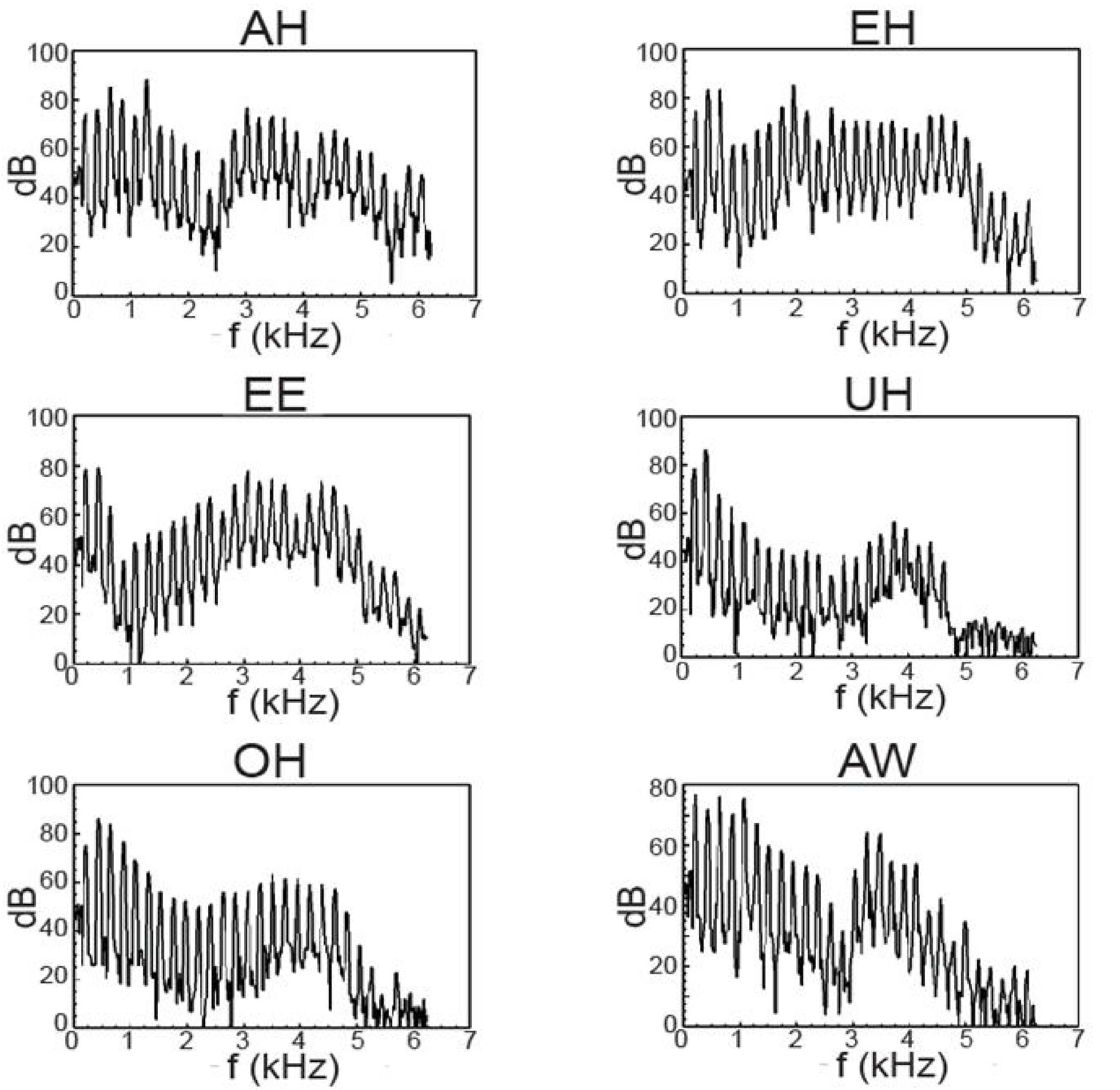

Figure 4 - Power spectra of six Italian vowels sung by soprano Emily Pulley on the note A 220 Hz.

The first peak of each spectrum is called the fundamental, or the first partial, followed by the second, third, and so on partials, all of which are located at a multiple of the fundamental frequency. The position of the fundamental corresponds to the frequency of the musical pitch; this will be designated as F0 in the formant analysis. If we draw a line through the top of the partials, we obtain a pattern, also called a spectral envelope, which is characteristic of each vowel. If we sing a vowel, we can have a reasonable idea what the spectrum would be like. Irrespective of the vowels, there are several features associated with all these spectra that can be considered the marks of a beautiful operatic soprano voice. The most striking is the very orderly gradual decline or rise in the magnitudes of the partials over a large frequency range. All spectra possess a good energy balance between the low frequency region (up to 1 kHz), which is required for the sensation of depth and sonority, and the mid-high region (2.5 to 4 kHz), which is essential for the good projection of the sound in a large auditorium. The spectra of AH and AW are somewhat similar but different from all others, since both are sung with an open mouth, albeit the tongue position in the latter is lower to the back. The spectra of OH and UH were also similar and most regular because there is only a minimal deviation in their respective mouth/tongue positions while singing them. The UH is the darkest sound by perception, and this is explained by the lowest emitted energy between 3 to 4 kHz. It ranks last in projection on the opera stage.

Because of the space restriction of this article, each vowel is represented only by one spectrum taken on a low note. In most cases these spectra give a good idea of how many formants a particular vowel has and where the formants happen to be. However, as pointed out by Müller [15], if a formant is relatively weak and its position falls between two partials, it might have no impact and be overlooked. This was the case for the vowels OH and UH whose second formants cannot be ascertained at the F0 pitch of 220 Hz, but become noticeable at the following notes of the scale.
It became obvious early in the course of this study that the small variety of Italian vowels would not be sufficient to categorize the large palette of tone colors the violins can offer. One had to look for vowels that exhibit major harmonic peaks and, accordingly, formants between 1000 Hz and 1600 Hz, a region where the violins tend to have considerable emission.

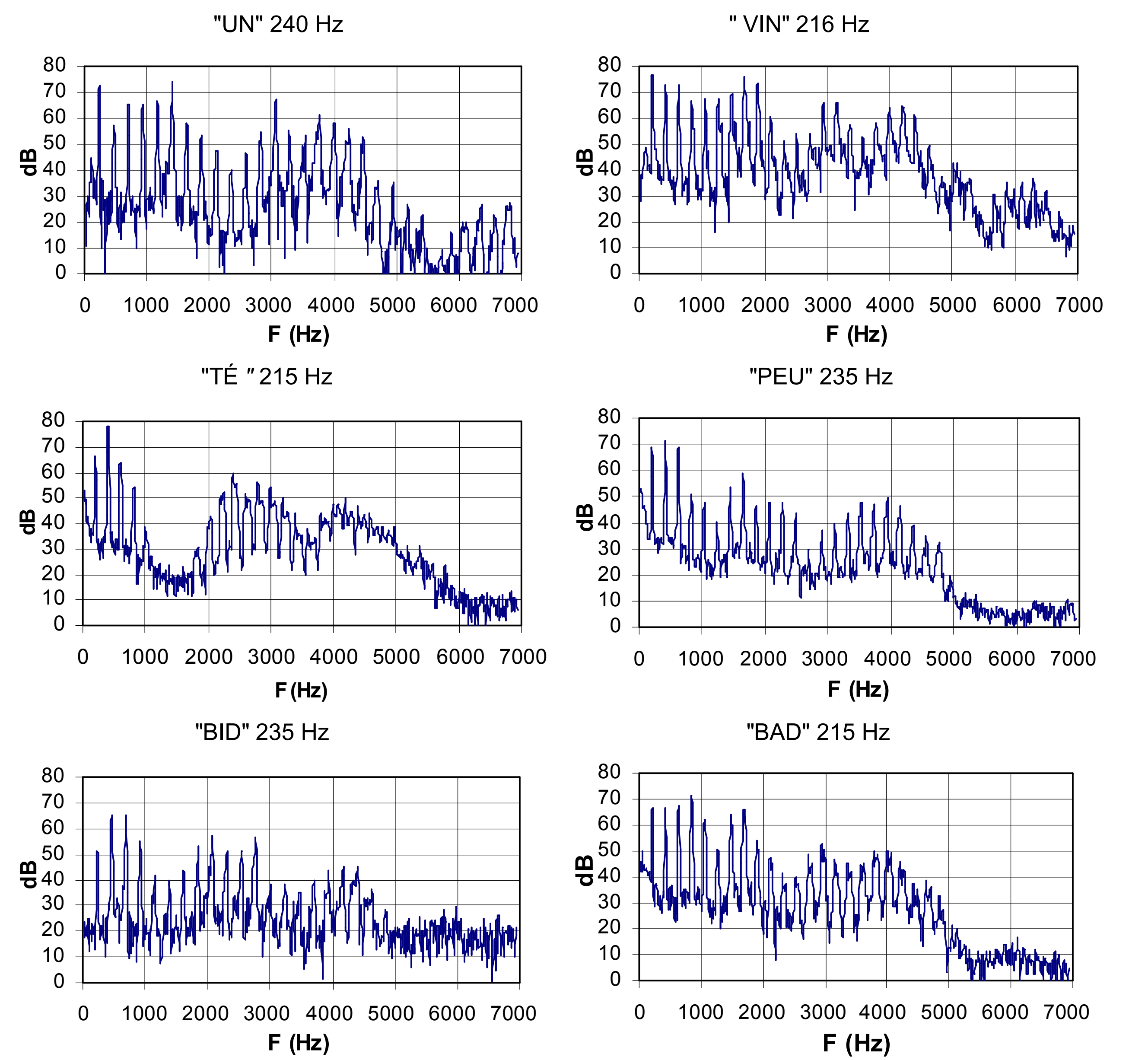

Figure 5 - Power spectra of some French and English vowels sung by soprano Emily Pulley

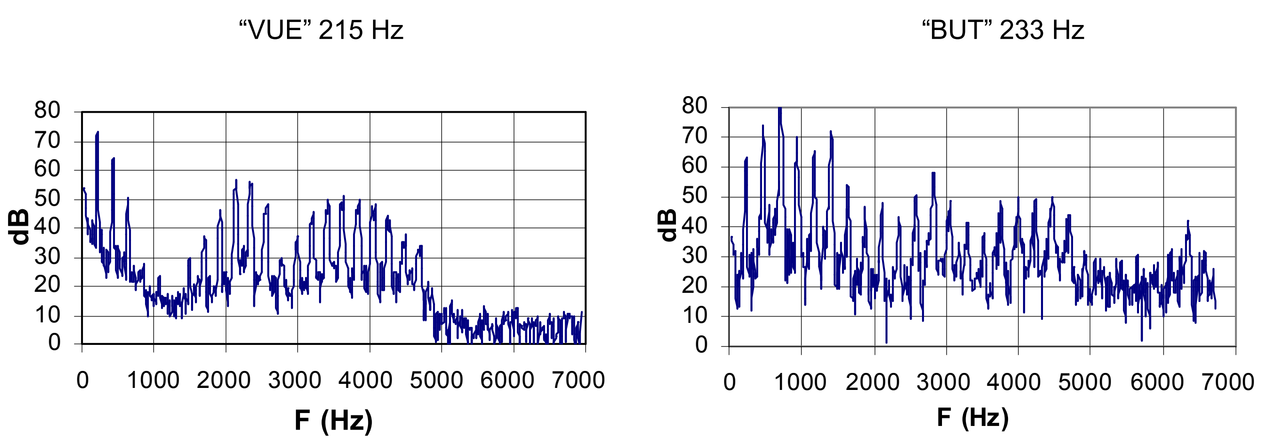

Figure 5 - (continued) Power spectra of some French and English vowels sung by soprano Emily Pulley

Figure 5 shows the spectra of eight vowels sung by Emily Pulley eighteen years after the recording of the Italian vowels, by which time her low chest tones became much darker. This may explain the strong first partials in some of the spectra, like the French nasal *UN* and *VIN*, although this might be also due to the nasality itself. These nasal vowels can be perceived in the tone of many violins, whose spectra also have peaks in the range that Dünnwald designated as characteristic of nasal sound. The strong spectral peak that could be responsible for this sensation lies between 1200 and 1400 Hz, a range where many violins also exhibit strong emissions. Considering the interpretation of nasality by Mores [17], one cannot be sure if this peak is the inevitable outcome of a strong airflow through the nasal passage, or it derives simply from the mouth-tongue positioning, and it would be the same with a closed nasal passage. It is noteworthy that the other nasal vowel, *VIN*, shows no peak in Dünnwald's nasal range [3].

Some explanation is in order for how the vowels in TÉ, PEU, and VUE were formed because there are several regional pronunciations for them. The É (the terminal vowel in the French liberté) was formed with a wide and slightly opened mouth, somewhat similarly to forming an EE. The vowel EU has a number of pronunciations ranging from a small round mouth opening, almost like in whistling, to a larger opening, like in the American form of bird, or pearl, and even larger in the posh Oxford pronunciation of the same words. Accordingly, the second major peak and formant can shift from 1900 Hz down to 1600 Hz. Ms. Pulley applied a medium sized mouth opening, which is better for the projection of the sound than the small opening. The vowel UE in VUE can also be pronounced in several ways, from a small whistling shape of the mouth to a wider opening, like in the Russian vowel "yeru". In both instances, the spectra are marked by a deep and wide trough between 1 and 2 kHz. The É and UE vowels show quite similar spectra, but the 1st partial dominates in the latter.

Among the three typical English vowels depicted in **Figure 5**, BID and BAT are the ones whose sound and spectra come close to those of many highly rated violins. The similarity of the spectra of the nasal French UN and the English BUT is quite striking. Although the vowel in BUT is not nasal, it has a strong peak around 1400 Hz, like the nasal UN, and this seems to support Mores's contention that nasality cannot be simply assigned to one peak in this area [17]. With a little practice, one can memorize the patterns of each vowel listed above with special attention paid to the location of the highest points and the troughs between them. The depth of the trough varies a great deal among the vowels, but the weak energy regions don't seem to play much role in vowel identification.

B. Power spectra of two violins by Giuseppe Guarneri del Gesù

The power spectra of a two-octave chromatic scale of the "ex-Sauret" Guarneri violin are compiled in **Figure 6**. We are fortunate that for this violin all notes of a chromatic scale are available for detailed analysis. As it was a common experience with other violins, the spectra of all the notes of the Sauret undergo a varying degree of change during the 2-sec time frame of a bow stroke, and the two bow strokes show some differences. For inclusion in **Figure 6**, I selected what could be considered the most characteristic spectrum. As we examine the progression of all these spectra from the open G 196 Hz onward, one is impressed by the regularity of certain patterns of the spectral envelope, especially in the low notes, where the partials are relatively close. We can see many similarities to the spectra of some vowels, and one can also specify certain differences. In the first and often strongest power domain of the violin—between 290 and 1100 Hz—the partials of some notes tend to alternate in dB-power, instead of changing gradually. Some abrupt changes in the shape of the spectral envelope can happen even in the mid and

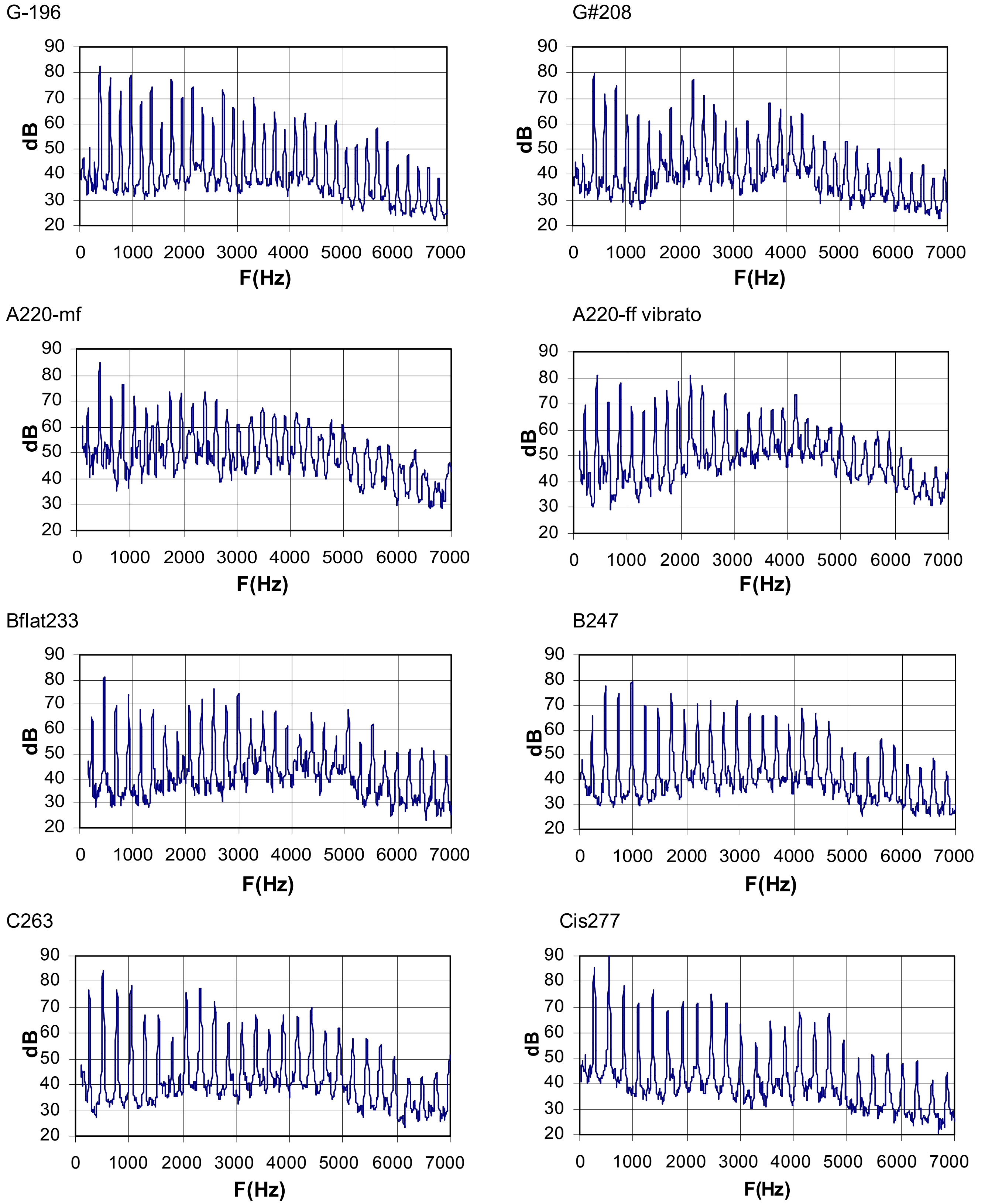

Figure 6 - Power spectra of the “ex-Sauret” del Gesù, played by I. Perlman

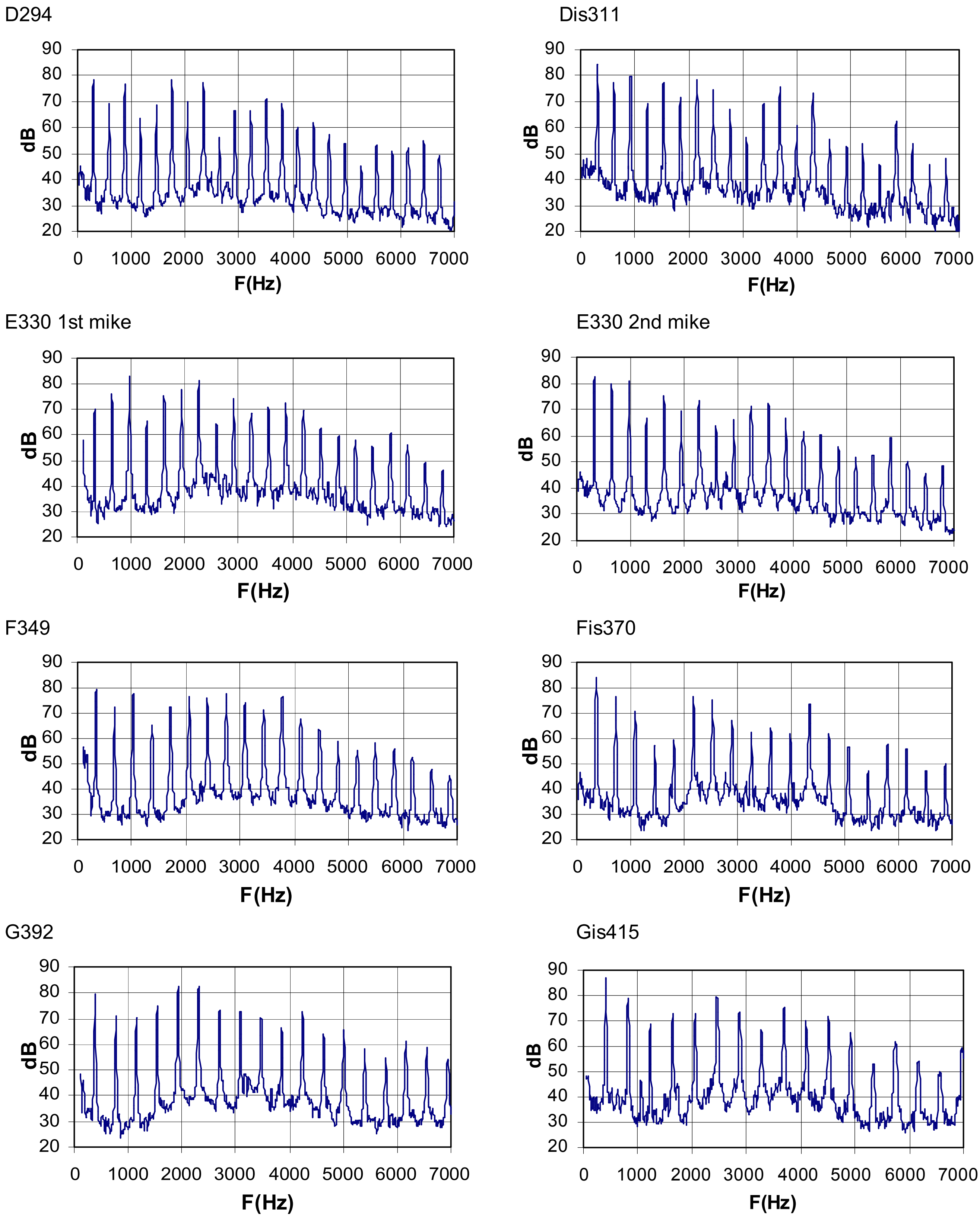

Figure 6 – (continued) Power spectra of the “ex-Sauret” del Gesù, played by I. Perlman

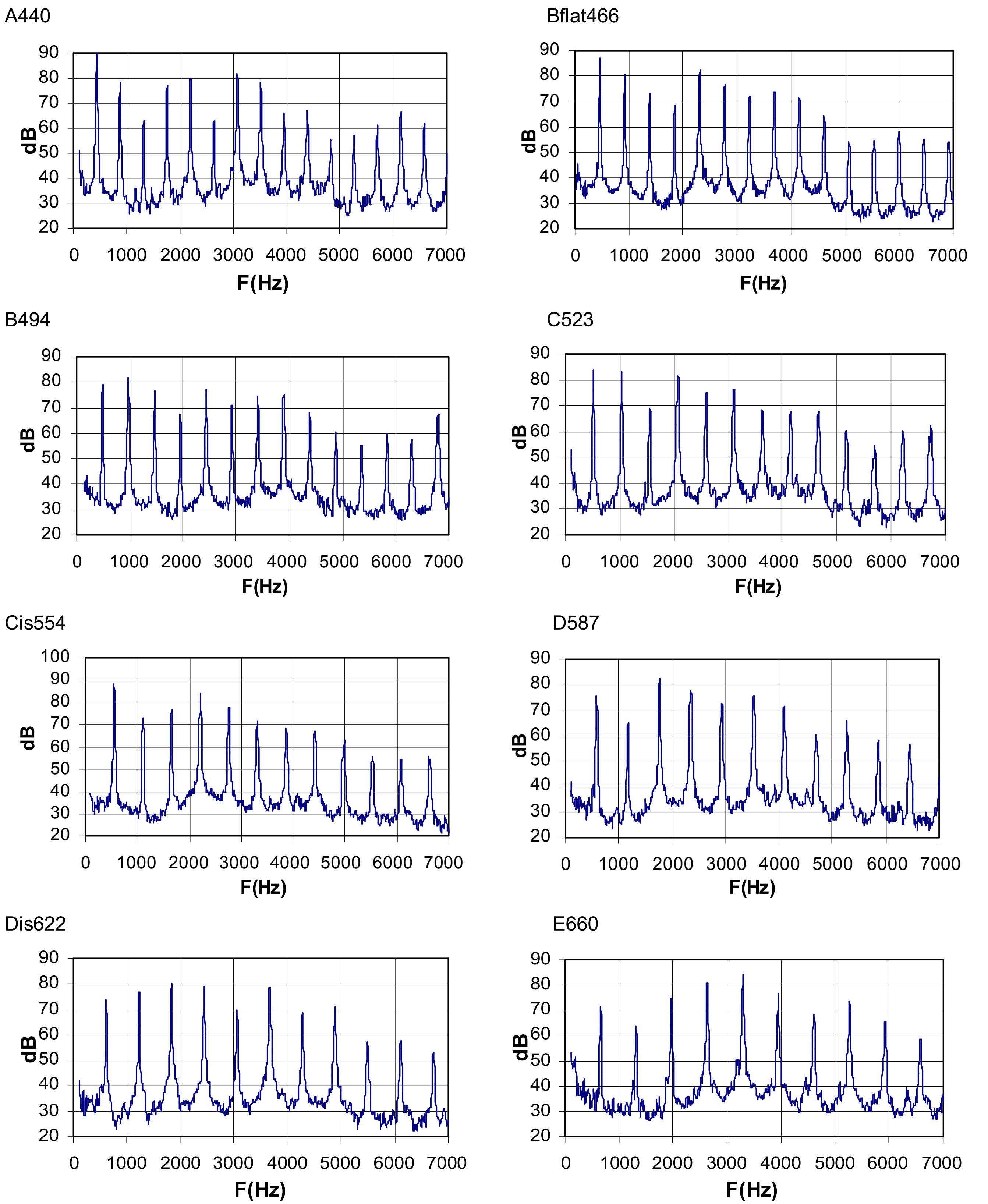

Figure 6 – (continued) Power spectra of the “ex-Sauret” del Gesù, played by I. Perlman

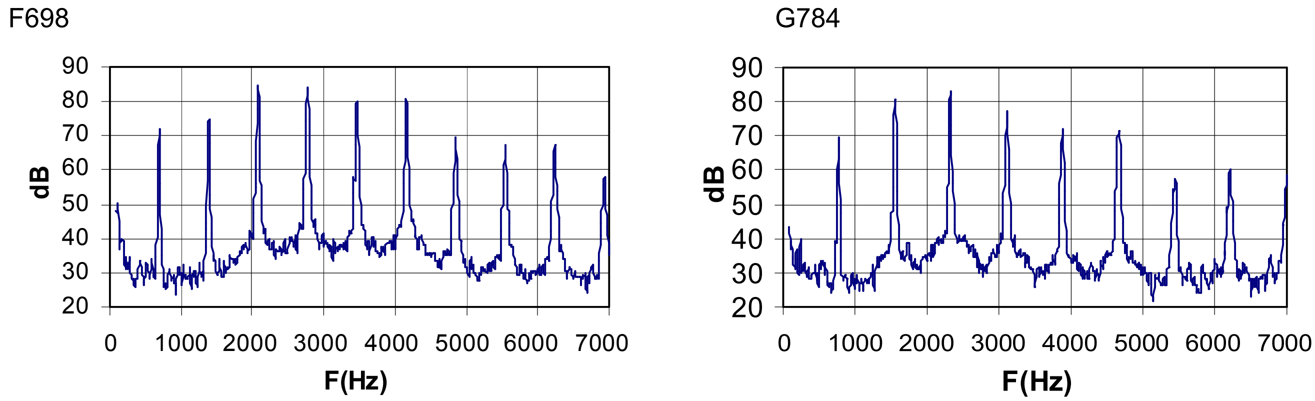

Figure 6 – (continued) Power spectra of the "ex-Sauret" del Gesù, played by I. Perlman

high frequencies in the areas where there happens to be a gap between the many localized wood resonances of the violin, or when a partial happens to fall on one of these resonance frequencies.

The spectra of the G# (Gis) 207 Hz and the A 220 Hz stand out as the most organized ones among all fine violins I have ever studied. The 2nd and the 4th partials are the dominant components because of the underlying strong body resonances, and the 3rd partials (Eflat and E, resp.) are weak. This strong first domain is then separated from the second strong domain by a wide trough of weak partials. The gradual changes from partial to partial in this second domain—like in the opera singer's voice—is very remarkable because we mostly observe this when famous players are playing famous instruments. The sensation of a singing vowel, variety of EH or AT, is unmistakable (go to Sound Samples). The spectra of Bflat233 and the C263 also reveal a notable organization in their damped sine wave patterns, the depth of the first trough, and apparent vowel-like spectral features. It is noteworthy that the 1st partial becomes stronger than the 2nd only on the open D 294 Hz, but even this note is quite bright because the 3rd and 6th partials are stronger than usual; the 6th partial is as strong as the 1st.

The first uncertainty appears at the note E 330 Hz, where the two microphones gave different magnitudes for the first three partials. Many violins do not have any major resonance at 330 Hz, and it is not unusual to find the 1st partial to be smaller than the 3rd one among modern violins. However, this is not typical of the old Cremona violins whose first partials somehow manage to slightly outgain the 2nd and 3rd ones. In the following F#370, G#415, A440, and Bflat 466 the fundamentals (1st partials) are strong and the pattern resembles a damped sine wave. Remarkable is the spectrum of G392, in which the higher partials are stronger than the 1st. The note B 494 Hz appears to be different from the norm, since the 2nd partial is stronger than the 1st. Apparently, the B-1 and B+1 resonances of the ex-Sauret are separated more than usual, as they appear to be located near A440 and C#554, and the B494 does not get enough support from them. Very surprising is the strong drop of emission beginning with D587 all the way through G784, whose weak fundamentals are followed by very strong 3rd, 4th, and 5th partial peaks. This may be a unique feature of the del Gesù violins, which we could not find in Strads. The note D#311, having strong 3rd and 5th partials, deviates most from the sine wave pattern. It would be intriguing to see if this power distribution is dominant, or it could be changed on further trials.

Power spectra of the "Ole Bull" Guarneri del Gesù were made from the wave file provided to us by Dr. H.C.Tai; they are shown below in **Figure 7**.

In his last violin, Joseph Guarneri, a great innovator, altered his model by cutting a longer than usual pair of f-holes and lowering the arching. Having made two copies of this model by my staff, and by measuring the sound of additional copies by J. B. Vuillaume and others, we are familiar with the acoustical consequences of this change. The emission at and around the air resonance is increased very significantly, as one might expect from larger f-holes, and so is the emission around the B-1 body resonance. Our listening impression of this model corresponds to a more masculine sound in the low register of the violin up to C526. (Go to Sound Samples folder). On the original instrument, not only is the 1st partial over-powering on the open D294, the 1st partials are also clearly dominant on the E330 and F349 notes which fall normally in a weak range of the frequency-response curve in most violins. The fundamentals are also strong in the A440, B494, and C526; the latter having spectral features that resemble other violins known to have a wolf-like sound on this note. Regrettably, we don't have the C# and F# notes available on

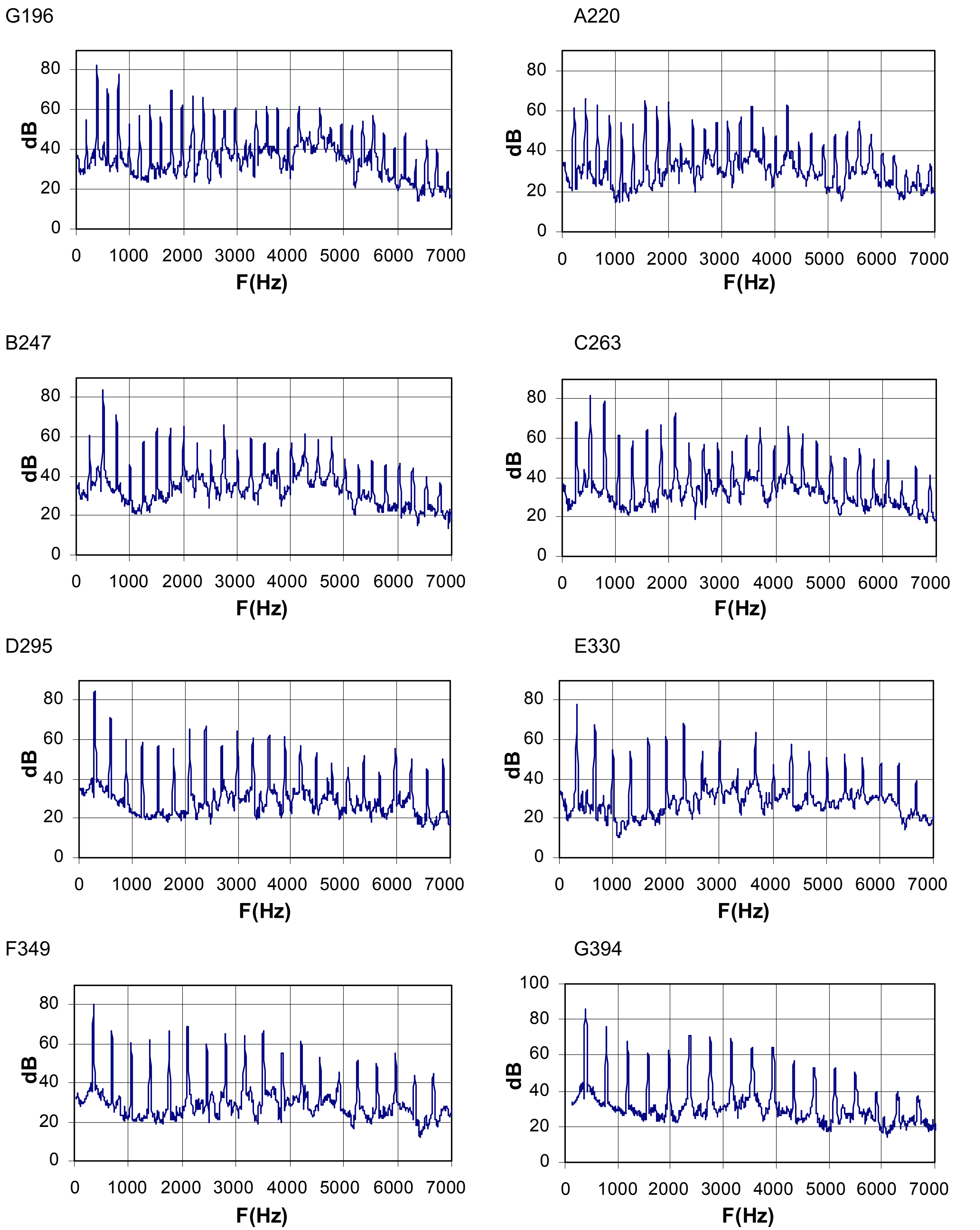

Figure 7 – Power spectra of the "ex-Ole Bull" Guarneri del Gesù violin; the notes of a C-major scale were played by Agnes Feng.

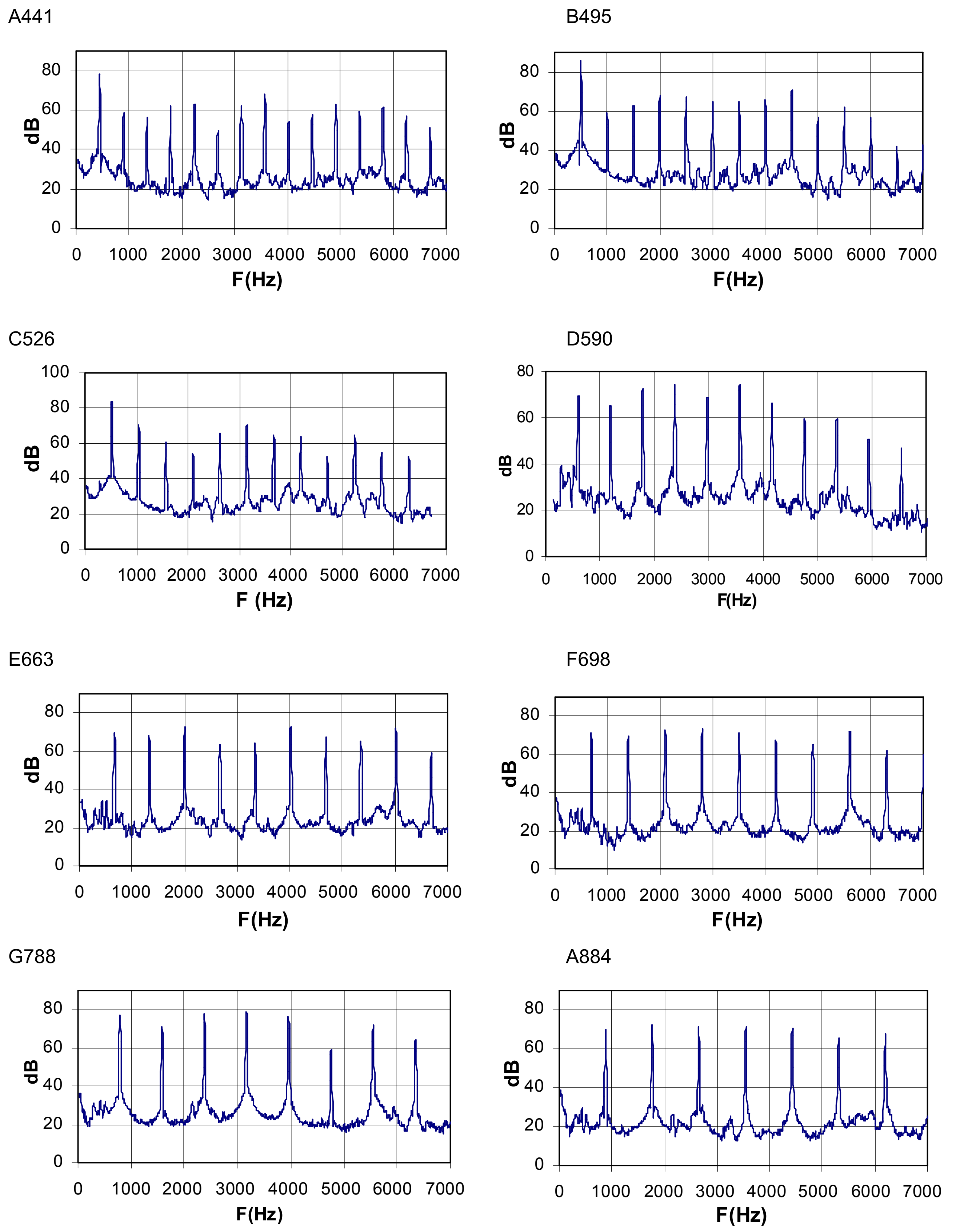

Figure 7 – (continued) Power spectra of the "ex-Ole Bull" Guarneri del Gesù violin; the notes of a C-major scale were played by Agnes Feng.

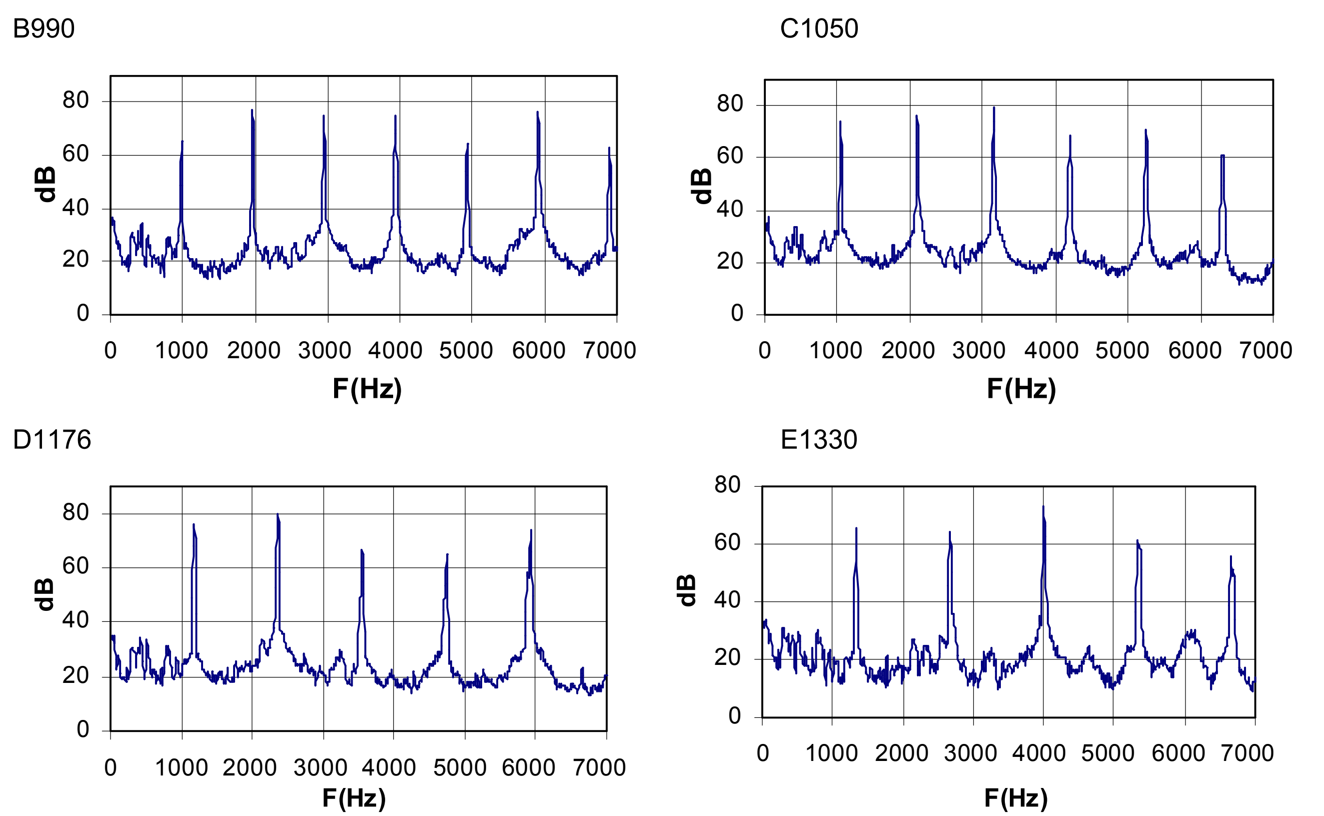

Figure 7 – (continued) Power spectra of the “ex-Ole Bull” Guarneri del Gesù violin; the notes of a C-major scale were played by Agnes Feng.

this violin that was recorded in Taiwan, but, on the plus side, we were given the wave file of a 3-octave C major scale.

On many notes one can see patterns in the partials comprising the first half of the spectral envelope—strong domains separated by numerous weak partials. It is instructive to compare the two Guarneris note for note to appreciate the differences. The ratios of the first five partials in the A220 are quite different, the Ole Bull having a pattern like the four fingers of a hand (minus the thumb). All the notes of the first octave have spectral features reminiscent of other fine violins in our database, as exemplified by E330 and F349. Like in the ex-Sauret, the D590 has a relatively weak 1st partial, but the low E string notes are sufficiently supported by their fundamentals. It is remarkable in all the high notes up to the E1330, the highest note reported here, to see a strong power emission even in the very high partials beyond 6 kHz. It is most exceptional to find the highest energy in the spectrum of E663 and F698 in the 6th and 8th partial, respectively. It is without any precedence in my experience that the largest peak of the E1330 spectrum would be the 3rd partial near 4 kHz.

C. Attempts to characterize the vowels in violins

The choice of vowels in this study was restricted to the vowels which are often heard in Europe, and one can reasonably assume that the old Cremona masters were exposed to people speaking the German and French languages. Each of these vowels is characterized by its individual power spectrum, as they are depicted in**Figures 4** and **5**. The first task at hand is to compare the spectra of our vowel library, which were provided by soprano Emily Pulley, with the spectra of the violins within the same frequency range. The number and position of the formants can be deduced, as a first approximation, from the shape of the spectral envelope. If there is a correspondence of the two types of spectra, then we can suggest the vowel of that particular note on the violin [19]. A quick perusal of the spectra of Italian vowels (**Figure 4**) and those of the two violins reveals that only two of the vowels, the Italian i and e (in our current designation EE and EH) show close enough similarities to violin spectra. The other Italian vowels have deep and often broad minima in the frequency range where the violins possess relatively high pressure amplitudes. For this reason alone, I did not expect to encounter the vowels AH, OH and UH in fine Italian violins. Fortunately, we do not need to consider the full frequency range that would encompass all four formants of a vowel, which has an upper limit somewhere below 5 kHz. It is an important practical observation of speech scientists that the first two formants can already define a vowel with 90% accuracy [15,31,34].

It may be no small surprise to connoisseurs that Italian violins have only few Italian vowels, and conversely it is remarkable that all the French and English vowels listed in **Figure 5** have their close analogs among the violin spectra. It deserves emphasis that it is in the low register of the violin where the vowel perception is the strongest. The reason for this is simple: when the partials are numerous and closely spaced as in the lowest notes, the formants are less difficult to identify. Once we arrive in the scale of notes at C523 as the fundamental frequency, we have only 5 partials below 3 kHz, and a formant could be overlooked if it falls in the middle between two partials. The E string notes of the violins all tend to sound a kind of EE, UE, and É or even indeterminate. A note of a violin in whose spectrum the partials have about equal amplitudes would not sound as any known vowel.

While my initial approach based on the inspection of power spectra has provided some ground for the recognition of vowels, the methods of modern speech analysis by linear predictive coding (LPC), as introduced to violin analysis by Müller and Mores [15] are clearly more powerful and give more confidence in interpreting the results. The algorithm of LPC (Burg) was developed for speech and not for violins, and it is not free of ambiguities. This is apparent both for the singer and the violinist as they progress on a musical scale from a low note to an octave and a half higher. The relative amplitudes of neighboring partials can change as they approach and pass the given fixed resonances of the vocal tract or of the violin. For this reason there will be a considerable shift in the frequency position of the first two partials. In order to remediate this problem, Pfitzinger developed two empirical equations [21], mentioned above, which we put to test in our present study. According to Pfitzinger, all important vowels of the IPA chart can be assigned a position in the trapezoid plot on the basis of three formant values, F0, F1, and F2.

A musical scale of each vowel listed in **Figures 4** and **5** and the French nasal MON were subjected note for note to the analysis by Praat, which provided us with the formants F1 through F4. The parameters for Praat were chosen according to Tai and Chung [18]. Normally, we selected the most typical value—just like we did for the power spectra—but also looked at the extreme values. For each vowel, we determined the respective formants for a number of notes; 8 notes in most cases, but we discarded the 2 or 3 extreme values. By filling the data into the Pfitzinger equations (see equations (1) and (2), p.6), we determined the *b* (backness) and *h* (height) values.

For example, the vowel EE was sung at the following five pitches of F0: 216, 247, 263, 294, and 330. The corresponding formants were obtained using the Praat program. The backness and height were calculated according to Pfitzinger for all five F0 frequencies. The numerical values are given in **Table 1**. Similar calculations were done for all the other vowels. The comprehensive vowel diagram encompassing all important vowels of European languages as sung in a projecting operatic voice is presented in **Figure 8**.

F0	F1	F2	*b*	*h*
216	399	2700	0.879	7.993
247	342	2733	0.5	9.775
263	456	2667	1.223	7.427
294	374	2679	0.831	9.528
330	444	2789	0.79	8.371

Table 1- Formants, and *b* and *h* values for the vowel EE.

Each vowel is color-coded by a symbol shown in the box on the right side. The position of the vowels within the diagram is shown by a cluster whose pieces correspond to the number of notes selected. Some of the clusters like BID, BED, and PEU are relatively tight and well defined; others, like the front vowel BAD, the nasal vowel VIN and the back vowel AW, are more spread out. The five lowest points of the stretched out cluster of the vowel BAD were taken on the high soprano voice of Kathryn Nagyvary. The differences in the size of her voice box and Emily Pulley's may explain the separation of their respective data points. A possible explanation for the scattering of the data points sung by Emily Pulley could be found in the observed reluctance or difficulty of sustaining the exact position of the mouth and tongue as the notes were being sung with increasing pitch and loudness. Sopranos cannot sing the low A 220 Hz as strongly as the note A 440. They also try to project the sound as well as possible, and this effort itself can result is some degree of distortion of the vowel. This may also be the reason why this vowel diagram of an operatic voice is somewhat different from the diagram of spoken vowels that were published by Pfitzinger [21] and Müller [15], whose front and back vowels are close to the front line and backline, respectively.

The front vowels according to **Figure 8** are EE (see), É (French *thé*), the English vowels in BED, BAD, and to a lesser degree BID. Exceptional is the high position of the vowel in VUE (ű in German and Hungarian), which can be sung with a small round opening. The back vowels are the English AWE, MOOS, OH (monothong) and the French AN, and MON. The height value of the u in Moos depends on the size of the opening; with a larger opening it would come down in the direction of OH. We expected these vowels closer to the backline. The central vowels are marked

VIN, PEU, UN, LOVE, and AAH, of which the first two partially overlap. The vowel of LOVE also overlaps with the back-vowel AW. The data points for the vowels OH and MON are also quite close.

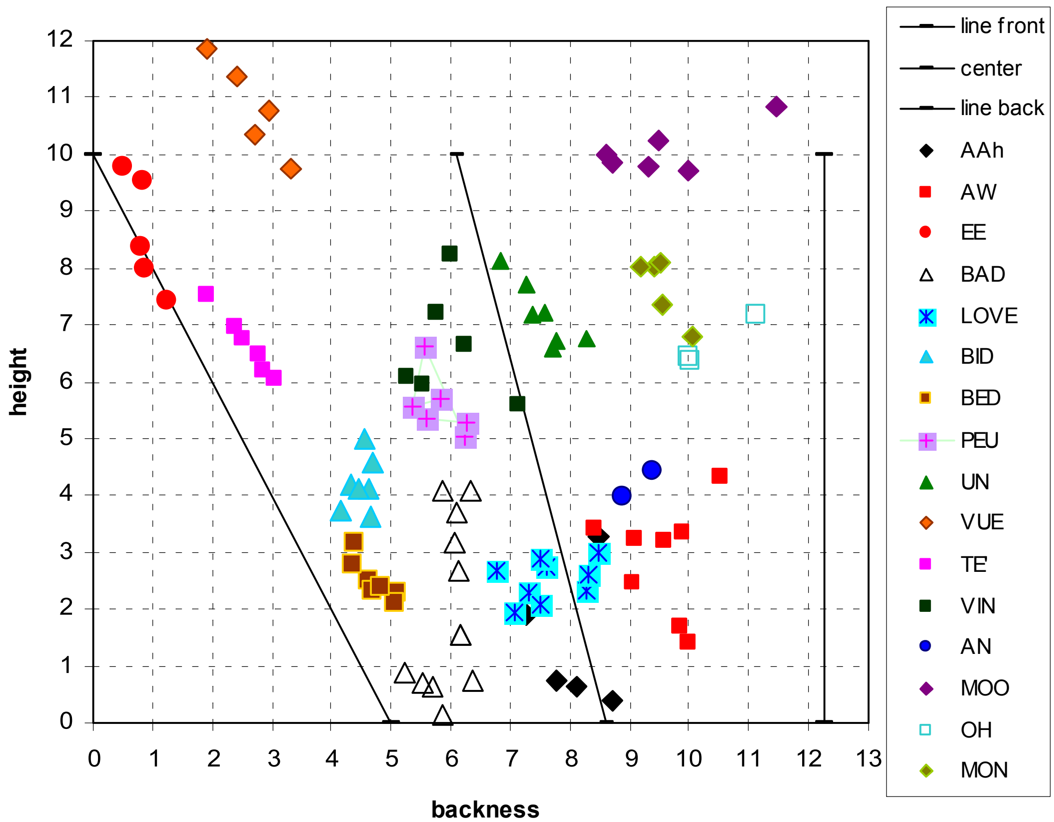

Figure 8 - The diagram of 16 sung vowels of the well-known European languages. The plot was made according to Pfitzinger [21]. Most vowels were sung by Emily Pulley, operatic soprano; the words BAD, LOVE and AWE were also sung by Kathryn Nagyvary, coloratura soprano, amateur singer.

The vowels of the Guarneri violins

In a manner similar to the analysis of voice, the notes of the violins were also subjected to the analysis by LPC with Praat in order to determine the respective formants. For many notes the formants were found relatively stable and unambiguous, while there were also some notes whose formant frequencies showed significant changes with time. This was in agreement with the observed changes in the power spectra of those notes, which can happen even in two bow-strokes of the same note. As an example of possible ambiguities, the differences between the first and second strokes of D294 and E330 of the ex-Sauret are shown in **Figure 9**.

The first bow-stroke of the open string D294 begins with four formants, but soon new transient formants appear, creating an unsettled sensation of timbre. The second bow-stroke is characterized by five formants, but their relative distances change considerably. The first stroke of E330 at the 2nd microphone is even more perplexing in its mobility of formants, and the discontinuity and splitting up of the formants. The most amazing of these changes is the splitting of the first formant; this seems to coincide with the onset of vibrato. Even in the second bow-stroke, only the first and the third formants are relatively steady; the slow shift of the second (F2) by as much as 500 Hz is responsible for the slight change of the timbre and the vowel one can perceive over the one second interval. This example serves to illustrate the complexity of the violin sound, and points to the difficulty of selecting a point in time when the formants have the most typical values. The relatively stable central portion of the first bow-stroke corresponds to the vowel in BED; the second bow-stroke is a nasal UN. The reader is invited to listen to these sound samples (See Sound Samples). Only by repeated bowings of the same note can the player settle on the most characteristic timbre and, implicitly, vowel of the particular note.

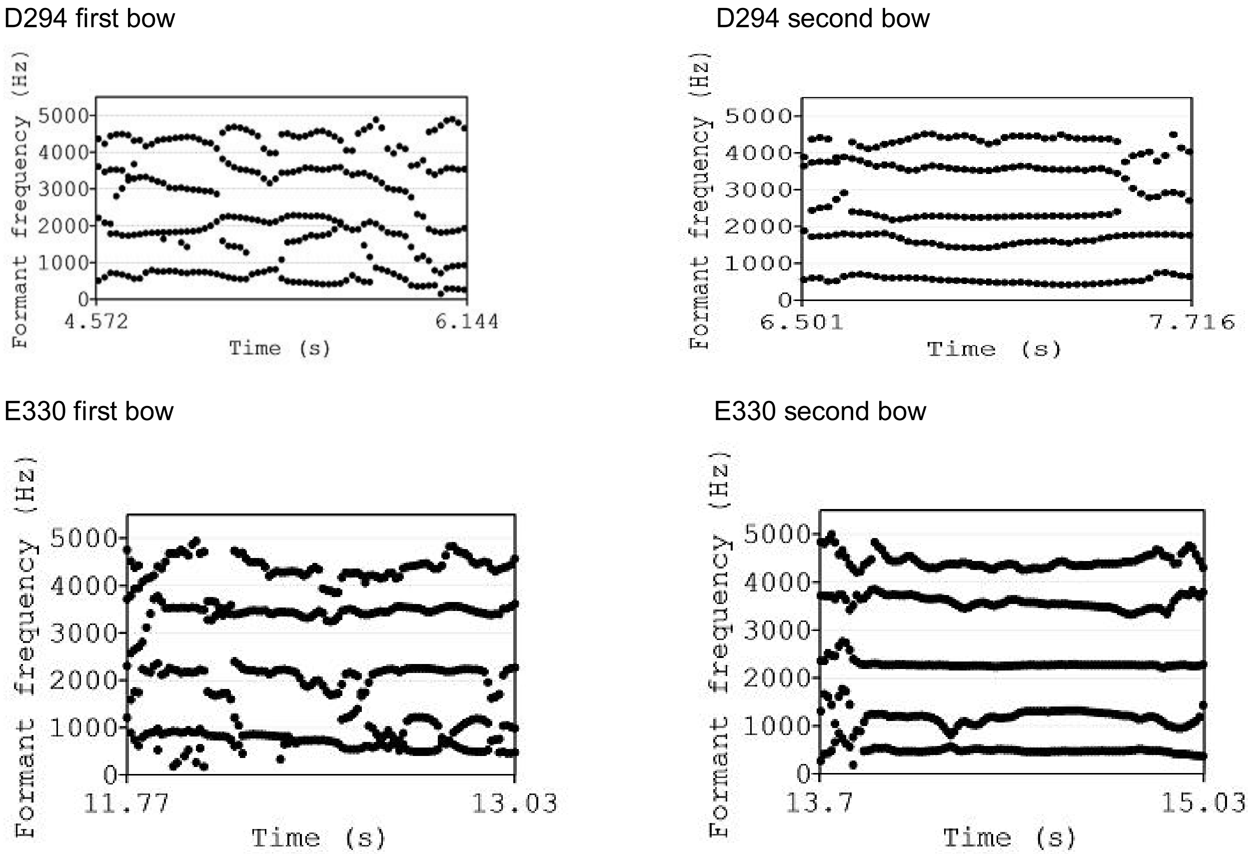

Figure 9 - The change of the formant structure in two consecutive bow-strokes of D294 and E330, played by Perlman on the “ex-Sauret”; sampling rate 11025 Hz, time window 0.05s (for D), and 0.025s (for E).

The second bow-stroke of E330 also demonstrates one notable difference between the formant structures of voices and the violins. The voice has only one formant under 1000 Hz and two formants under 2000 Hz. In rare occasions and for a brief period of time, the violin note can have two formants and three formants, respectively, in those two domains.

In the following, I have applied the methods developed by Pfitzinger [21] to position the low register notes of the two Guarneri violins on the same vowel template that was established using the soprano singing (**Figure 8**), henceforth called the Pfitzinger plot. The notes available to us from G196 up to C526 were fed into the Praat program in order to obtain the most characteristic values for the formants. As mentioned above with regard to the unsteadiness of some formants in **Figure 9**, there were a few instances of ambiguities in making the best choice, and in such cases we also examined the power spectra of all critical sections. The shortcoming of the formant-versus-time diagram is that it does not show the relative strength of each formant. It is the power spectra and the LPC spectra that clearly reveal which formant is weak and negligible, and when two formants are essentially fused together. The parameters required for the Pfitzinger plots are the values for F0, F1, F2, the backness, *b*, and the height, *h*; these are compiled for the "ex-Sauret", and the "ex-Ole Bull" in **Table 2**. We examined 12 notes for the "ex-Sauret"; we had only 11 notes at our disposal for the "ex-Ole Bull" that was recorded in Taiwan [18] (the F#370 is missing).

The selection of the formants for F#370 of the "ex-Sauret" requires some explanation of its formants versus time diagram (**Figure 10**). In the middle of the bow-stroke the formant F2 disappears for a while and then returns. If we accept this unstable F2, which fluctuates between 1200 and 1400 Hz as the proper basis of our calculation, we would have to assign to this note the vowel character of the French UN. However, the power spectrum clearly shows that this F2 is insignificant in its pressure amplitude, the 1st partial and the one around 2200 Hz being the dominant ones. The typical spectrum of this note is the one deriving from the middle of the bow-stroke, which is shown in **Figure 6**. This spectrum corresponds to the vowel in VUE (with a touch of PEU in it, sung with a small and round mouth opening), and this is the sound we can actually identify. For this reason, we opted to list the F2 at 2275 Hz.

"ex-Sauret"							"ex-Ole Bull"						
F0	F1	F2	F3	F4	*b*	*h*	F0	F1	F2	F3	F4	*b*	*h*
196	715	1759	2786	3798	5.61	2.53	196	648	2073	2183	3748	4.02	3.40
220	557	2091	2865	4276	6.30	2.60	221	660	1814	3153	4108	5.20	3.62
247	855	1994	3012	4130	4.85	1.67	248	513	1816	2988	3238	4.74	6.20
263	514	2204	3526	4492	3.08	6.37	263	570	1368	2037	3828	7.37	5.45
294	436	1616	2293	3558	5.46	8.17	295	345	2175	3035	4315	2.48	10.28
330	929	2175	3024	3961	4.25	1.84	331	397	2295	3489	4365	2.27	9.37
349	867	2205	3493	4062	4.01	2.63	349	379	1864	3640	4259	3.98	9.95
370	422	2275	3227	4364	2.46	9.18	394	464	2594	3640	4305	2.98	4.10
392	463	1972	2688	3968	3.85	8.54	441	451	1745	2832	3442	4.86	9.14
440	476	1875	2169	3594	4.34	8.65	494	501	1976	2701	3890	3.98	8.56
494	850	2030	3298	4300	4.68	3.89	524	530	2117	3167	3921	4.18	4.79
523	672	2059	3226	4239	4.14	6.15							

Table 2 - Formant, backness and height values for calculating the Pfitzinger plots of the "ex-Sauret", and the "ex-Ole Bull" del Gesù violins

Repetition of a bow-stroke was also instructive for getting a variety of the open D295 note in the "ex-Ole Bull" violin, the only violin whose D295 was played four times. The fourth bow-stroke in one of the two close microphone positions shows an interesting shift of the formant traces **(Figure 11**). The great variation of the F2 value imparts a slight diphthong character to the sound, which observation is also supported by the changes of the power spectra at 1200-1500 Hz. (See and listen to Sound Samples).

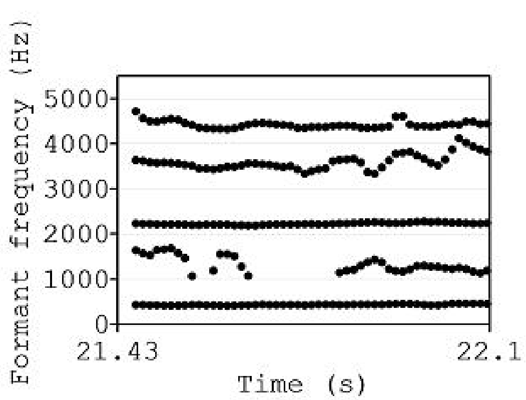

Figure 10 - Formants vs. time diagram of note F#370 Hz of the "ex-Sauret"

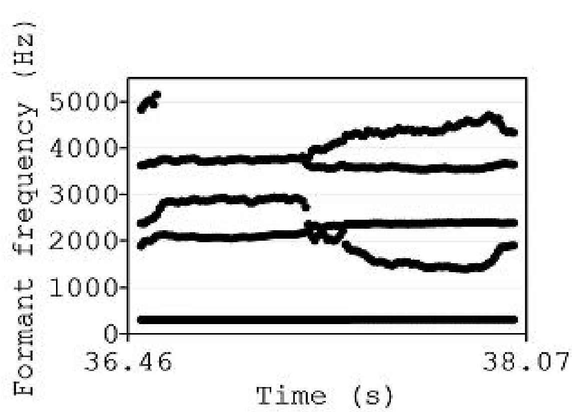

Figure 11 – Formant structure in the 4th bow-stroke of the note D295 of the "ex-Ole Bull"

Employing once again equations (1) and (2), we have constructed the Pfitzinger plots, i.e., the quantitative vowel diagrams for the "ex-Sauret", and the "ex-Ole Bull" violins (**Figure 12**). They are quite different with regard to the space that is occupied or not occupied within the *b* and *h* coordinates, and also with regard to the place where the same notes of the violins can be found. The identity of each note can be determined by the *b* and *h* values listed in **Table 2**. For an easier perusal, to each spot was added the designation of the note, with Go, Ao, Bo, and Co standing for the notes on the G string, and the same letters with the suffix 1 standing for their higher octave.

Both violins have all of their examined notes positioned between the front line and the center line, i.e., they have no back-vowels. Apart from this similarity, there are significant differences in the distribution of the notes in a way that fits their perceived soprano and mezzo-soprano character.

The ex-Sauret has 5 notes under *h*=4, corresponding to vowels sung with an open mouth, and 6 notes above *h*=6. The notes that are closest to the front line are, in increasing order of height, the B247, E330, the F349, the G196, the B492, the A220, the C263, the C523, and the F#370. The vowel of each note can be decoded by holding this map of violin notes against the vowel map of Emily Pulley. If we compare the positions of the notes with the vowels of the soprano vowel diagram (**Figure 8**), the first group of 5 low-height notes would line up within the vowel ranges of BAD, BED, and BID; the A220, the C263, and the C523 would be BID; the F#370 would be an EE. To the right of F#,

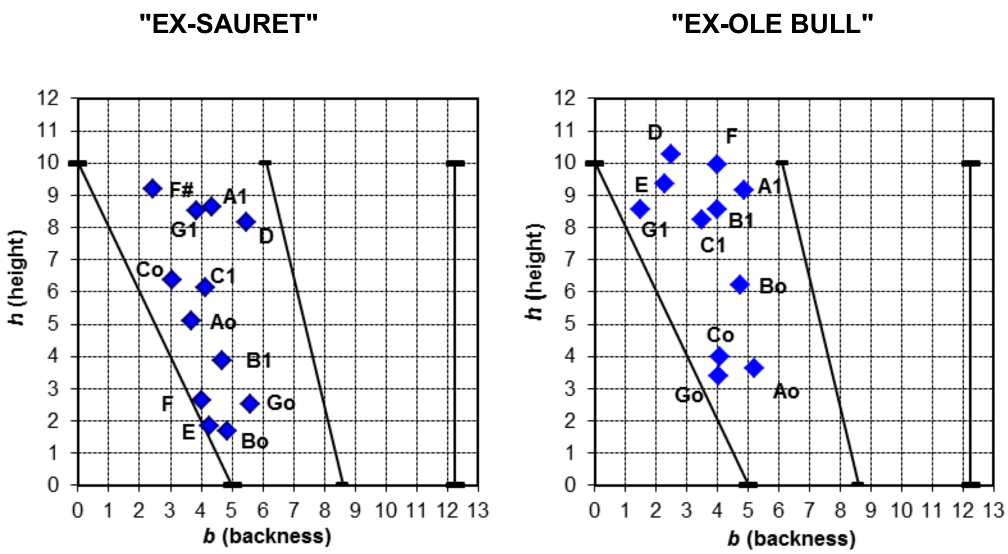

Figure 12 - Pfitzinger plots of the two Guarneri violins. The suffix o (like Go through Co) designates the notes on the G string; suffix 1 indicates the notes of the higher octave.

there are three notes in the upper part of the graph above *h*=8—the G392, A440, and D294—which correspond to a transition between VUE and a German-Hungarian variety of ***ő*** (PEU sung with a small round mouth opening). The upper four notes have very strong fundamentals in their power spectra. It is noteworthy that the two C notes are close to each other, and should possess similar vowel characters, while the two 'G's and 'A's are quite distant. All the notes in the bottom group have small fundamental peaks in their power spectra. As was shown in **Figure 6**, the power spectra of note E330 were somewhat different at the two microphone positions. The formants and *b* and *h* values given in **Table 2** correspond to the spectrum at microphone 1 (the close one). A part of the note at microphone 2 corresponds to *b*=7.4 and *h*=7.7; its position in the Pfitzinger plot would be a nasal UN.

The last violin of Joseph Guarneri, "the Ole Bull", occupies a unique place in the oeuvre of this iconoclastic master of Cremona. Our analysis of the lowest 11 notes by Praat confirms the aural impressions and provides a novel way of characterizing them in a most unusual Pfitzinger plot (**Figure 12**).

The 11 notes are distributed in a top-heavy fashion according to the height coordinates. Only three notes—G196, A220, and C263— are in the lower left area of the diagram under *h*=4, neatly grouped together; they can be mapped to the vowels BED, and BID, and with some overlap to BAD (see **Figure 8**). The note B248 at *h*=6.2 is a transition between the two extreme poles; the site can be considered a hybrid between BID and PEU (sung with a half-open mouth). Well separated from these four notes is the group of seven packed together in higher positions on the vowel diagram. Nearest to the front-line are G394, E331, and C523 whose positions are near to vowel EE. The B494 appears to be a hybrid between EE and VUE (like the Russian vowel yeru, *ы*). The location of A441 and F349 corresponds to the extremely focused EU/ő (small round mouth opening). As shown in **Figure 11**, the open D294 note of this violin has two options for the F2 formant. The one included in **Figure 12** (*b*= 2.48, *h*=10.280) sounds like the French VUE; the other one (*b*=5.0, *h*=10.2) is closer to the center-line, occupying the hybrid position between the French UE and EU (perhaps with a judicious sprinkle of OO in it).

At this point, it is advisable to go back to the power spectra of the "ex-Ole Bull" shown in **Figure 7**, which show very strong fundamentals (1st partials) of the notes from D294 up to C526. For these and many other notes of this violin, one can specify the corresponding vowel simply by the comparison of their spectra with those of the vowels of Emily Pulley. Clearly, the method employing the Pfitzinger plot is more quantitative and informative, but uncertainties remain in both cases.

D. The role of the F1 formant

When we look at all the information presented above about the two violins, one can find an important difference at their emission in the low frequency range. This can be further illuminated by plotting (F1 - F0) versus F0 (i.e., the musical pitch of the note) as shown in **Figure 13**. The notes that lie low on this graph, especially those with the ordinates under 200, tend to sound—in my own terminology—dark, "fat", and sonorous; they are well supported by strong first partials of their FFT spectra. High values of F1 - F0 correspond to notes with a more shallow and thin sound, whose first partials are smaller than the second. Once again, readers can listen and make their own characterizations. The two violins vary in their number of such fat notes and their locations. The "Ole Bull" has more of them-—the notes D, E, F, G, A, B, and C. In some aspects of its sound, the "Sauret" resembles Stradivari violins. It has a thin soprano voice on the G196, A220, B247, E, F, and B492; yet on the notes F#, G392, and A440 it also has a dark, alto-kind sound, and its F1 - F0 is near zero. It is remarkable that the trend from note to note can be sometimes gradual, but also abruptly large. For example, the "Sauret" ordinate value at B247 is the highest, but it drops precipitously to C263; then it makes the largest jump from D294 to E330. Based on my subjective listening and observation over many years, I conclude from this set of experiments that the position of F1 relative to the F0 (the pitch of the note) may be a factor in lending a degree of sonority, darkness or the opposite, i.e., a lightness to the sound, and thus influence our perception of its being soprano or alto.

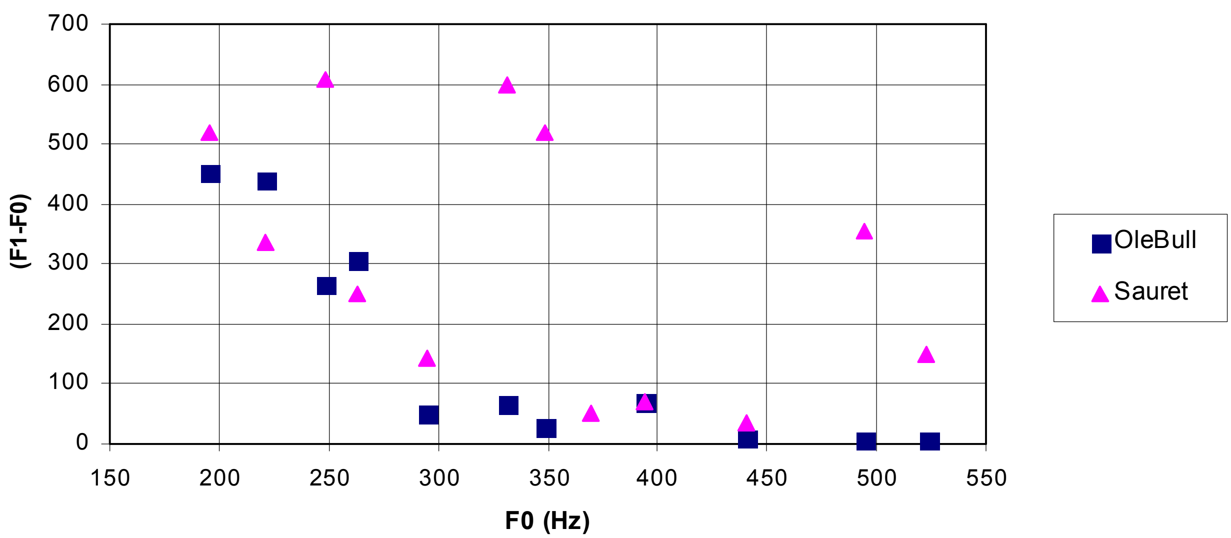

Figure 13 – The plot of (F1 - F0) versus F0 for the two Guarneri violins; F0 is the musical pitch of the note.

IV. Discussion

A. The power spectra

The tone quality of violins is clearly a very complex matter, and all approaches and claims dealing with it should be critically examined for their validity and relevance. A recent paper of Harris and Fahy has raised serious questions about the validity of the popular objective test involving an impact hammer [25], but theoretical reservations were already expressed back in 1996 [19]. More researchers are starting to accept the notion that the quality of violins can be studied during the course of playing them, even if the results are less strictly reproducible. The methodology as described above combines the essential subjective elements of playing and making choices with physical-instrumental assistance. The results are as yet preliminary, and they have to be backed by a larger number of experiments by the present author and others. In considering the respective merits of the fully objective approaches and the subjective-objective hybrid method described above the reader must weigh accuracy versus relevance with regards to tone quality as it is understood not only by scientists but also by the players and connoisseurs of the violin. The weaknesses and drawbacks of the subjective methods that were utilized in this study have been described in detail in section A2 of this paper. However, uncertainties come with the territory also in other areas of physics, and the essence of the violin is its sound as being played at a high level—an inherently subjective element.

One should not underestimate the significance of having the power spectra of Perlman's "ex-Sauret" available on a two-octave chromatic scale (**Figure 6**), which should be of great interest to all violinists and makers since no such data have yet been published. The spectra of this violin are the most valuable in my collection of violin spectra with regard to the regularities within the spectral envelope. On many notes, the pattern of the spectral envelope resembles a damped sine wave, a feature first observed and postulated by E. Rohloff [9] as the mark of an excellent violin. The existence of such a regularity in the gradual progression of the partials constitutes a strong argument that room acoustics could not have been a major impediment since it is more likely for such random external factors to create disorder than order; dissimilarity than similarity.

A noticeable peculiarity of the "ex-Sauret" is a transition in the general character of the sound spectra that begins with the D 586 Hz. Many notes of the octave below this D, except E330 and B494, are well supported by fundamentals and have good sonority, while from D586 up to G784—the last note recorded—in all notes the first partials are smaller than the second or the third. According to my own taste and experience, one can make the following general statement: when the 1st partial is much smaller than the 2nd partial, the sound tends to be shallow and not as sonorous, as the other way around. Adjectives like thin and fat also come to mind, but the readers are expected to come to their own characterizations in this regard after listening to the notes in the Sound Samples folder. The extraordinary brightness of the E string notes could have been only in part due to the reverberant nature of the dressing room, because the enhancement of the 3rd, 4th and 5th partials (in the range of 2 to 4.5 kHz) on my own violin in the hands of Mr. Perlman were less impressive. Neither was Mr. Perlman able to reduce the strong emission of my new violin in its "nasal" range beyond that of my own usual offering. (Listen to the Sauret-Nagy comparison on the note A220: vowels BID and UN, respectively). In two respects the violin can over-rule the intentions of the best players: one cannot fight the effect of a large resonance maximum, and one cannot create a strong partial at a frequency in a deep trough between resonance peaks.

We have no reason to think that the results of the ex-Ole Bull violin could have been jeopardized in any significant manner by the acoustical peculiarities of the Chi Mei concert hall. One of the author's violins was played along with 12 famous violins from the collection, and none of them showed noticeable effects of standing waves or obvious interference. The spectra of the Ole Bull (**Figure 7**) are consistent with what we would expect from this particular model of Guarneri del Gesù. The large air resonance caused by the long f-holes and the low arching of the belly enhanced not only the D294 but also imparted large 1st partials to the E330 and F349 notes. I suspect that the extraordinary large 1st partials of this violin on some notes could have been, in part, due to the player, Agnes Feng, using a shoulder-rest. I have made two copies of the Ole Bull model which had similar general characteristics to the original in this low to mid octave register; however, the 1st partials were less overpowering when the violins were played without a shoulder-rest. The notes from the D587 on throughout the E string are again very bright with significant power even at 6 kHz. The strongest partial of E663 is at 4010 Hz. As in the Sauret, once again we have encountered a sudden break in the tonal character at the same point, the note D586, which designates the start of a succession of notes that sound thin because the higher partials are stronger than the fundamental. The dichotomy between the broad mezzo sound of the low register and the extreme brilliance of the entire E string range is a striking feature of the “Ole Bull” Guarneri del Gesù. This is noteworthy because I could not find any modern violin with the combined attributes of having strong fundamentals on the D string and weak ones above D586.

The spectral features of these violins are in many regards similar to those of the operatic singing voice, and this observation should be helpful in predicting the tone quality of a violin merely on a visual basis by examining its power spectra of notes. One benefit of recording power spectra of many violins is in developing a sense to connect certain audible qualities of sound with a given pattern of the spectral envelope. With enough experience, a person can make predictions in both directions: from sound to spectral features and vice versa.

B. The identification of vowels in violins

In addition to presenting power spectra that could be considered as standards of excellence, this paper is also an attempt to provide a new framework for analyzing the violin tone relying on some established concepts in voice acoustics.

My original approach to seek the identification of a vowel from a note of the violin was to compare its power spectrum with those of the voice vowels sung at the same pitch [19]. This simple method provided a few unambiguous identifications among many tentative ones, and some of the readers might be satisfied just doing that. An alternative to manual inspection is to apply LPC/Praat formant analysis, and the latter is clearly a more scientific approach, even if it is not free of ambiguities.

The vowel diagram in **Figure 8** represents, to my knowledge, the first attempt to place a large number of vowels sung by an outstanding operatic soprano into the quantitative 2-D framework of the IPA vowel diagram according to the method of Pfitzinger [21]. The underlying equations provide some degree of compensation for the change of the ground frequency F0, and some vowels are indeed packed neatly together.

One has to keep in mind that the formant analysis employed by Tai and Chung [18] that we have also elected to use, LPC with Praat, was conceived and written for the human voice, and therefore it cannot be always expected to deliver accurate data when it is applied to the notes of violins. Its use is justified by the perhaps lucky coincidence that both the voice and the violin possess four significant formants in the frequency range of our interest. Complications can arise from the violin having a few minor formants, i.e., formants with much less power in the LPC spectrum, which occasionally can be confusing.

The first formant (F1) values are determined by the lowest 5 resonances of the violin [1-7] as the musical scale (F0) progresses from G196 upwards. During this process the fundamental and its immediate overtones (partial1 through partial4) approach and pass over the strong resonance peaks, causing a change in the relative amplitudes of the harmonic partials which, in turn, determine the value of F1. In our experience, the formants versus time traces of Praat showed little variation for F1, and we consider the F1 values quite reliable. However, general understanding of the resonances above B1+ is limited, and that is where complications arise, mainly with regard to F2. Most violins can have a number of strong resonances between 800 and 1000 Hz, and again between 1200 and 1500 Hz, although these are much less noticeable in the famous Italian violins played by top soloists. Some of these resonance peaks happen to be in the range that is responsible for the perceived nasality of sound one can hear in many modern and some old violins. The "Titian" Stradivarius which was studied among other violins in the VIOCADES program [2, 23] has several strong peaks in this less desirable range of its response curve. When a harmonic partial of the fundamental, especially on the D294, E330 and F349, comes close to one of these less well defined resonances, it brings about a low value of F2, which in turn leads to a high backness value, and possibly could be perceived as an AW, UN, AN, ON or UH. Such vowels are frequently encountered in commercial instruments, but they are much less audible in the old Italian violins. There is no straight forward explanation why the great Old Italian violins are often less nasal than some new ones; the underlying "bridge-ring" resonances are not well understood.

The Praat program examines the power spectra, as if they had originated from a human voice, and extracts the formants accordingly. The weakness of the formants versus time diagram (like **Figures 9-11**) is that it does not indicate the power relationships between the four formants. Occasionally, and fortunately not too often, the F2 assignment by Praat may cause a discrepancy between the assignment of the vowel and the one the listener can actually hear. Our dilemma in choosing the correct F2 is explained in the following.

The significance of the power relationships of partials and formants was already emphasized by S. Müller [15], who assessed this relationship on the basis of the LPC spectra, which are derivatives of the FFT power spectra. According to Müller, the attention of our hearing and nervous system is called to the formants powered by strong partials to the possible neglect of those that have weak underlying partials. Specifically, there are uncertainties when a weak F2 is close to the 1000 Hz upper limit of the first strong frequency domain of F1. In such cases, the listener can be persuaded to lean towards either of the two options—accept the weak F2 in the nasal range, or ignore it and assign the F2 designation to the formant that was originally F3. In a generalized way one can say that if a formant of weak power falls between two formants of high power and close to one of them, it might be overwhelmed, and it can go unnoticed unless one listens for it carefully. The F2 formants can fluctuate significantly and even disappear for a while as is shown in the F#370 of the ex-Sauret (**Figure 10**) and in the D294 of the Ole Bull (**Figure 11**). On careful listening, these notes give the vowel sensation of a diphthong (go to Sound Samples). This observation suggests a new way of appreciating the complex and flickering beauty of the violin tone, in which the modulation of sound by vibrato includes a fluctuation of volume, frequency, perceived vowel, and high frequency emission. To my knowledge the phenomenon of diphthongs is a new addition to the understanding of the violin's tone.

My choice of the Praat program was occasioned by the persuasive conclusions of Tai and Chung [18] whose LPC/Praat parameters I was also using in most of my measurements. More recently, I was advised by Professor R. Mores to experiment with other settings of the Praat program that would be more in line with the extremely high soprano nature of violins. Specifically, the gender "female soprano" setting of Praat was changed from 600 Hz to 750 Hz and even up to 1000 Hz; the prediction order was reduced from 16 to 11, which required the adjustment of the sampling rate to 11025 Hz; the upper limit of analyses was 5500 Hz. The outcome of these changes was 1. a significant smoothening of the LPC spectral maxima, 2. an increase in the number of formants, whose traces with time became less shifty. The significance of these changes in the LPC settings has yet to be sorted out because they gave rise to new complications. Among the unusual findings was the occasional appearance of two formants between 1 and 2 kHz—something that we have not encountered with the operatic vowels. This would be in accord with two auditors reporting the hearing of two different vowels, or possibly hearing two vowels at the same time. A negative finding associated with the extreme increase of the gender/order adjustment was the appearance of stable formant traces which imply a static nature of the overall timbre, and this was not in agreement with the changes of the FFT spectral partials. I measured the formant values under two sets of conditions, in both cases keeping the gender width of 600 Hz, 1. setting a prediction order 11, sampling rate 11025 Hz, and time window 0.05s, and 2. the setting used by Tai and Chung [18], i.e., order 16, sampling rate 44.1 kHz, and time 0.15 s. The values were essentially the same.

The assignment of vowels via the Pfitzinger plots reveals both similarities and great differences between the two violins. The vowel content of both violins encompasses the vowels that lie between the front-line and center-line of the operatic vowel diagram (**Figure 8**). The ex-Sauret is the more balanced violin with regard to the diversity of vowels; it has more notes at low height values, i.e., notes that sound like vowels sung by a wide-open mouth. As I intend to detail in a later publication, this positioning makes the ex-Sauret relatively similar to some Strad violins. The Ole Bull is unique in the sense that 7 of the 11 notes analyzed are high front vowels, which must be due to their having high fundamental emissions.

It is not yet apparent from the data of these two del Gesù violins, but my recordings of many Strads, Guarneris, Guadagninis and other outstanding violins [36] have already provided some evidence that the great masters of Italy could have had their preferences for certain vowels in the sound of their violins. The low notes, especially, the A220 almost always appear in the realm of the open vowel as in BAD or BID. This note is prominently played three times in the Kreisler cadenza of the Beethoven concerto, and it lends itself to comparing the violins of many famous artists on their CDs [37]. It is noteworthy that the A220 played by Perlman, Mutter, and Oistrach on their Strads, and Stern on his del Gesù all sound like BAD and exhibit spectra very similar to the ones given here for the ex-Sauret. Apparently, the very different recording environments did not cause a noticeable distortion in the part of the spectral envelope that determines the vocality of the sound. The vowels BED, BID, TÉ, EE, VUE, and PEU, all appear in the low and mid register of the great Italian violins. The definite identification of vowels near the center line, be they sung by a soprano or played on a violin, is quite challenging even to experts of phonetics. Violins seem to exude a multitude of vowels which are not included in human languages. It is possible that the old Masters had less appreciation for the vowels near the back-line of the diagram; we might hear them only for a split second, or in certain acoustical environments from a distance. In new violins, we have encountered OOs, OHs, ANs, and AWs under our usual measuring set-up at close distance. These happen to be the vowels that do not project well.

It is not without irony that what we commonly call the "old Italian sound" is not devoid of a French accent; this is probably an intrinsic property of the construction and materials of the violin. Cremona had been occupied at one time by both the French and the Austrians, and thus the Cremonese people were familiar with these languages. The makers might have liked the EU and UE vowels, but less so the nasal ones. We don't know how much the vowels have changed after having gone through the hands of French and English restorers, who might have had their own preferences of vowels. We have reasons to believe that the insertion of large sound-post patches, which can be found in the vast majority of the old violins, could have added more nasality to the sound by increasing the stiffness of the bridge area; my own experimentation with adding sound-post patches to new violins resulted in an increase of nasal emission. The strong nasality of many modern violins could also be due to the increased thickness of the center favored by the makers of the last century and many contemporary makers.

There is one intriguing aspect to the discovery that the violins of the great Cremonese masters have a specific vowel content. They had no SpectraLab and Praat at their disposal, but it is not an unreasonable assumption that they possessed a highly refined sense of hearing that would have allowed them to discern a vowel in the low octave of their violins. We know now, and it is well illustrated in the figures above, that each vowel represents a definite power spectrum. In absence of any scientific instrumentation, Guarneri del Gesù and Stradivari had to do no more than to ascertain that each note of their violins sounded like the vowel they had in mind for it. The reproduction of selected vowels could have been the ultimate validation of their final product, whose manufacturing, of course, could have involved a process control of many standardized factors.

A particular set of vowels could be a defining determinant of tone quality of a violin, one of the first impressions one might get on hearing the notes. A practical outcome of this research could be a broad effort for the characterization and identification of violins by their respective Pfitzinger plots. However, there is clearly more to the tone quality of a fine violin than a sense of its vocality. A pleasing set of vowels must be coupled with the presence of brilliance in the tone, which is essential for the superior projection expected of a great concert instrument. I assume that the great makers worked intentionally on adjusting the vowels of a violin by shaping its arching and thicknesses, but the brilliance of the sound was more of a material property deriving from the wood processing, and applying the filler and the ground. Factory violins that lack the proper filler and ground possess little emission at and above 4 kHz [3]. According to Tai and Chung [18], the exceptional brilliance of the best Stradivari violins can be attributed to their high average F3 and F4 values, which are higher than those of violins by other makers. Our hearing is very sensitive with regard to the frequency position of a formant, but the brilliance of the great violins could also be due to the higher formants having great pressure amplitudes.

Recent work of Smit *et al.* suggests that the F3 formant could have a role in the psychoacoustic perception of vowels [38]. Their results point to an important deficiency in our current methodology, which is the lack of expertise in psychoacoustical research. We can only hope for a contribution of others in setting up panels of phonetics experts, including also children and musicians, and conducting a proper psychoacoustic evaluation of the various violin notes to see how their subjective perception correlates with their position in the Pfitzinger plot. Furthermore, F3 should be taken into consideration whenever there is any ambiguity in characterizing a vowel in a violin note.

V. Conclusion

The research described in this paper was intended to fill an existing void in an area of great interest to all those who make and play the violin, which is the assessment of tone quality by a method that is readily accessible to everyone. It applied the objective scientific method of sound analysis by FFT spectra and the method of speech analysis by Praat to evaluate the tone quality of the bowed instrument note for note in actual playing. Thus the approach has both objective and subjective components, whose strength, benefits, and limitations should be apparent to the reader. It is for the first time that the analysis of a chromatic scale is presented in the most fortuitous manner, when both the violin and the violinist represented arguably the very top level of world-class. The subjective approaches for the analysis of tone quality [12-19] based on actual playing are always coupled with a degree of uncertainty, but the results are probably more comprehensible for violinists.

My work was conducted towards achieving two specific goals. First and foremost, I wanted to provide sets of power spectra to serve as a sort of standard of excellence, a graphic representation of each note. The quality of spectra reported here represents the best in my data bank of violin spectra. These spectral images can be used by makers who wish to compare the corresponding spectra of their Guarneri copies and assess their success of reproducing them. Anyone wishing to make a tonal copy of a particular Strad or del Gesù would have to go beyond producing a vaguely similar response curve; a more rigorous burden of proof would require furnishing a set of power spectra. The value of the response curves taken on Stradivari and Guarneri violins by the impact-hammer method [23] could be validated by averaging the spectra of a chromatic scale of bowed notes on the same violins.

Such series of spectra serving as standards of excellence could also be an important tool in teaching the art of violin playing to students whose tone production needs improvement. In my experience, a student can achieve amazing progress by playing into the spectrum analyzer in real-time and trying to shape the pattern of harmonics to come close to the selected spectrum of excellence. The violin may not sound like a del Gesù, but its tone color can be always optimized by bio-feedback.

The second goal was the more accurate identification of the vowels one can hear when the violin is played slowly in a scale. The results are best displayed in the diagram that was devised by Pfitzinger [21]. One common feature in the respective diagrams of the two violins is the location of the two lowest notes, G196 and A220, in the area of the vowel A as in BAD; also the open D and A notes fall near the top in the area between VUE and PEU. All notes have a position in the diagram, albeit some of those vowels are not easy to pronounce. There is a great degree of difference in the overall map positions of the notes, creating a kind of fingerprint, and this has the potential for the identification of violins. Since the bowed violin note is never static but ever changing to some degree, some notes can shift their location for a fraction of a second into a more nasal domain close to the right side of the center-line in the diagram. We could not find stable back-vowels in the above Guarneris. They are extremely rare in old Cremona violins recorded at close distance; in far space locations everything else is possible.

It is intriguing to consider the possibility that the vowel assignments in these violins are not coincidental, but the result of the intentional design by the maker. Stradivari, Guarneri and some other period makers in Italy could have used vowel identification as a quality control, a stamp of approval. The French restorers could have played a role in modifying the vowels of the violins.

This work should be viewed within the framework of the previous long-standing efforts to describe the tone quality of violins. Since FFT based spectrum analyzers can be downloaded free on the Internet, the above approach should have an appeal to those who are not much interested in the complexities of acoustical science. The first part dealing with FFT spectra is very user-friendly, and could be easily adopted by makers and players. The second part that relies on the methods of phonetic analysis is more complex, and it will have to be elaborated and further developed by an interdisciplinary approach, a collaboration of speech scientists and violin researchers.

Hopefully, my results with a similar description of violins of Stradivari, Guarneri, other Italian and French makers can soon be published, and the reader will have a more comprehensive view of the tone quality and the vocality these instruments possess. In future publications I hope to extend the present methodology to include a discussion of the reproducibility of spectra in the hands of different players in different acoustic environments. The role of the set-up also remains to be clarified.

Acknowledgments

The seeds of this project were planted in the late 1950s during my student years in Zurich, Switzerland, by the violinist Brenton Langbein who claimed that his Strad possessed a set of recognizable vowels. I am most grateful to Dr. Robert Kenefick for thirty years of moral support and encouragement to continue with this unpopular research project, and also for building the anechoic chamber. I am grateful to Texas A&M System Chancellor P. Adkisson, University President Frank Vandiver and Dean E. Hiler for granting permission for violin research and providing a quiet field lab, following the recommendations of Lord Menuhin, Isaac Stern and Ruggero Ricci. I can't thank enough the artists who provided the essential sound samples, Mr. Itzhak Perlman, and Ms. Emily Pulley, in Texas, and also to Dr. H.C. Tai and Ms. Agnes Feng who made available the recording of many violins from the Chi Mei Museum of Taiwan. I also benefited from the in-depth discussions with Dr. Tai concerning the suitability of Praat for analyzing the sound of violins, and with Dr. A. Buen about the response curves. I am also grateful to Dr. Robert Mores for sharing his insights and experience with the problems of applying LPC analysis to violins. My wife Mary Ann and my daughter Kathryn provided useful soprano vowels and a keen perception for tone quality.

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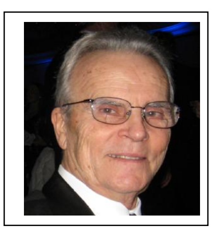

A native of Hungary, Joseph Nagyvary majored in chemistry at the University of Budapest (1952-1956); he became a student of the Swiss Nobel Laureate Paul Karrer in 1957, and received his PhD in the chemistry of natural products in 1962. While in Zurich, he had his first formal violin lessons on a violin which once belonged to Albert Einstein, a coincidence which helped turn his attention to the physical mysteries of the violin. He gained his first glimpses into the art of violin making from the Zurich luthier Amos Segesser. For his discovery of the structure of the curare poison, he received in 1962 the annual award of the Swiss Chemical Society, which led him to spend a postdoctoral year in Cambridge with Lord Alexander Todd, a British Nobel Laureate. He came to the United States in 1964, and settled down in Texas in 1968 where he was tenured in 1972 as professor of biochemistry and biophysics at Texas A&M University until his retirement in 2003. Dr. Nagyvary was the recipient of a Career Development Grant, and numerous other research grants from the National Institutes of Health, the National Science Foundation, and NASA. His scientific expertise includes the chemistry of alkaloids, nucleic acids, origin of life, and the role of dietary fiber. His discoveries concerning the classical violins were made public in 270 lectures sponsored by the American Chemical Society and the Sigma Xi. Dr. Nagyvary was the invited representative of violin science at the "Strings and the Universe" program of the World Year of Physics, Dec. 14-15, 2005, in Tokyo, Japan. He received the gold medal of the Japanese Physics Society for his discoveries of micro-composites and nano-composites in Old Italian varnishes.