# THE APPLICATION OF NONINVASIVE ACOUSTIC MEASUREMENTS TO THE DESIGN, MANUFACTURE AND REPRODUCTION OF BRASS WIND INSTRUMENTS

**Philip A. Drinker and John M. Bowsher**

The design and manufacture of musical instruments have evolved over the centuries as arts based on the knowledge, skills, and intuition of the makers. One aspect of manufacture can be especially challenging: reproduction of an original instrument, such as a trumpet or serpent, that cannot be measured internally without disassembling or cutting it open. Repair and restoration pose additional problems, particularly in the case of an unplayable antique, that may even have parts that are missing or that are of questionable authenticity.

The value of a noninvasive measurement technique for design and reproduction will be evident to all who have tried their hands at instrument making. One of us OMB), working at the University of Surrey, has had a long-standing interest in the development and application of such techniques, and in some of the related problems of defining the determinants of quality in brass wind instruments. [1] We describe here methods based on impulse reflection response that allow us to calculate an instrument's impedance—or resonance—characteristics, as well as graphical reconstruction of its bore profile. The mathematical foundations for these measurement techniques are complex, and have been reported in the acoustics literature. [2] Our purpose here is to report the practical results achieved so far, without bogging the reader down in theory, and to demonstrate the applicability of these techniques to instrument design and reproduction.

Impulse response has been used in diverse applications ranging from seismic prospecting[3] to studies of the human airways, [4] vocal tract, [5] and the oro- and nasopharynx, [6] as well as the properties of auditoria [7] and of loudspeakers. [8] While its theoretical basis has been known for many years, the large amount of mathematical processing required kept it from practical application until computers became widely available and rapid signal processing techniques were developed. [9] The tests shown in the following sections were each completed in two minutes, using a small personal computer (BBC Master 128); performed manually, a single experiment would have required many hours, and the calculations about six months.

## ACOUSTIC MEASUREMENTS

When a brass instrument is blown, the player's lips, acting as a vibrating valve, create a train of pressure pulses which travel down to the bell, and are then largely reflected back to the mouthpiece, with only a small portion of the energy being radiated as sound. The train of pulses contains a broad spectrum of frequencies, and the determinants of the relative proportions of the harmonics in the radiated sound lie in the geometry of the air column and the mechanisms of sound transmission in air. One of the most widely studied—and perhaps most useful—properties of a brass instrument is its input impedance profile (Figure 1), because of its close relationship to the series of tones that can be sounded. Acoustic impedance is a measure of the opposition to the passage of an alternating pressure signal (a sound) through the instrument. It is defined as the ratio of the oscillatory driving pressure, *p,* to the instantaneous volume velocity, *U.* Thus, impedance, Z=*pill.*The input impedance is the impedance looking into the mouthpiece end of an instrument. It is determined by the bore (or internal configuration), frequency, and the velocity of sound in air. In brasses, on which our work was focused, impedance is greatest at conditions of resonance when the alternating pressure is at a maximum for a given flow input. It should be noted that for instruments like the flute, which are open at both ends when being played, the conditions of resonance are for the input impedance to be at its least.

Peaks in impedance occur when the reflected wave is exactly in phase, or in step, with the incoming wave; the pressures in the two waves are additive, and thus support, the action of the player's lips. With a well-designed instrument, this occurs at frequencies which are approximately whole multiples of a fundamental frequency. In a primarily cylindrical instrument, such as a trumpet or trombone, this fundamental does not coincide with the lowest-frequency impedance peak, but with more conical brasses (e.g., the baritone horn), the fundamental is closer it. Between the impedance peaks, the valleys represent frequencies at which sound production is not supported, because the injected and reflected waves are out of phase; at low values of impedance, most of the energy simply leaks out the bell. It should be noted, however, that many skilled brass players can, in fact, produce tones in regions where the horn does not normally sound. Because the lips have a relatively great mass in comparison to the mass of the air column, they can dominate its behavior, and the impedance profile of the whole system, comprising horn, mouthpiece, and lips, can be shifted significantly. Of course, these shifts cannot be measured with laboratory apparatus of the type described here since they depend on the very close mutual interaction between all parts of the system.

The input impedance profile, as shown in Figure 1, can be determined in several ways. The earliest method, used with modification by most workers up to the present time, is based on excitation of the instrument by an external sound source, and measurement of pressure and flow at the inlet. The excitation frequency is varied to scan the playing range of the instrument, and the impedance at each frequency is calculated from the ratio,p/U, measured at the inlet. Measurement of Uis particularly awkward and many experimenters merely try to keep it constant at an unknown value; obviously they can then record only comparative data. Although simple in concept, these measurements, which are said to be in the frequency domain, are difficult in practice, and take many hours to complete; they are therefore susceptible to environmental changes that affect the velocity of sound in air during the experiment, thereby introducing significant error into the results. It should also be noted that frequency domain measurements ofimpedance do not directly provide information on the internal configuration of the instrument.

In an alternative method, in which the acoustic measurements are made in the time domain, the instrument is excited by a short sound pulse containing the full spectrum of necessary frequencies (Figure 2). The injected pulse is reflected back from each point in the instrument where there is a change in impedance produced by a change in cross section, and the reflected signals are recorded by arrival times (Figure 3a). This reflection record is treated mathematically to remove the effects of the shape of the input pulse, by a process known as "deconvolution." The resulting record of impulse reflection response (Figure 3b) contains the data allowing computation of the input impedance profile, with the frequencies of the impedance peaks and their amplitudes, as well as calculation of the bore profile. The recorded data show arrival times of the signal reflected from each point in the instrument where there is a change in impedance (i.e., cross section). Using the speed of sound in the calculation, the arrival time data can be converted to distance or position within the bore; the cross-sectional area at each point is calculated from the magnitude of the local impedance as determined from the impulse response.

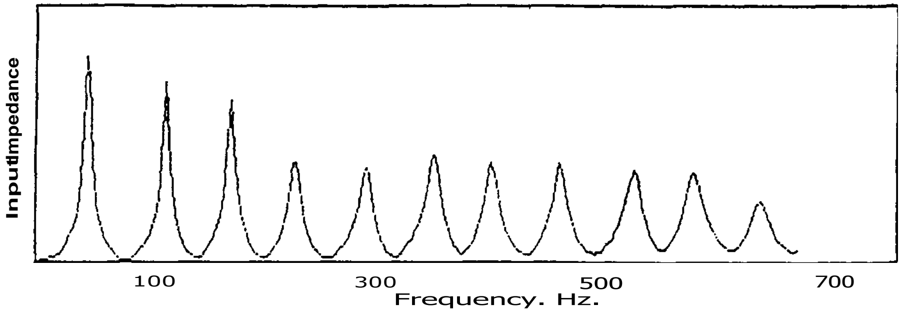



**Figure 1**
Example of an input impedance profile (trombone).

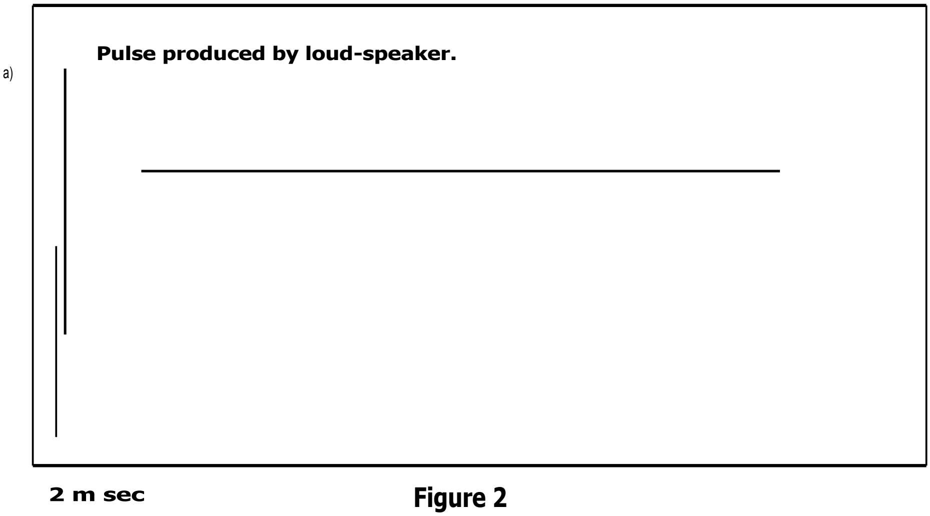
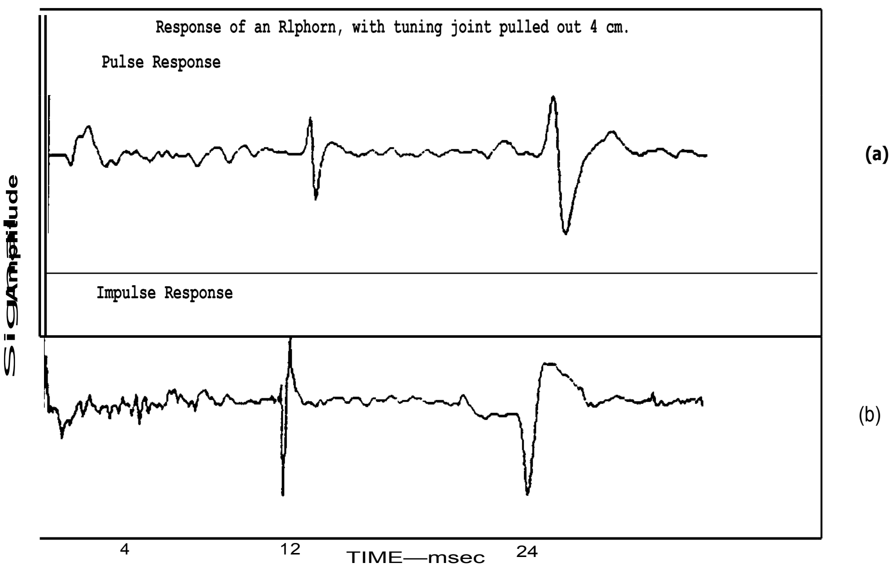



**Figure 2**

The input pulse used to produce the trace in Figure 3a. Figures 2-4, 7, 10-13, and 15 are from Bowsher, "Impulse Measurements on Wind Instruments." Used by permission.




**Figures 3a, 3b**

(a) Pulse response of an alphom, measured with the tuning joint pulled out 4 cm, to show a landmark that could be identified (the spike at the midpoint of the trace).

(b) The impulse response, calculated from the data in Figures 2 & 3a.

## EXPERIMENTAL METHOD

Figure 4 shows a block diagram of the measurement system used in these studies. The cylindrical source tube, incorporating the sound source and microphone, is attached to the instrument being studied (without mouthpiece), using a smooth transition to prevent unwanted reflections. In operation, a two-millisecond pulse (a sharp click) generated by the computer is emitted by the source (a tweeter loudspeaker) and travels down the source tube into the instrument under study. Figure 2 shows the form of the pulse injected into the instrument as picked up by the microphone, and displayed by the computer (uncalibrated signal amplitude). The pulse form, necessary for the deconvolution computation, is obtained before each experiment by blocking the end of the source tube, and recording the reflected signal which is stored in the computer. When the pulse is injected into the instrument, it is reflected at each point where there is a change in impedance; the return signal (Figure 3a) is picked up by the microphone and stored by the computer. The computer control of the experiment facilitates signal averaging to reduce the effects of ambient noise; each measurement is based on a train of pulses (usually 250), and the raw data are averaged prior to computation. With the data displayed in Figures 2 and 3a, the deconvolution yields the impulse response (Fig 3b).

It is important to realize that the reflected acoustic signal will be re-reflected by both source and microphone, and will travel up and down the system until it dies out. The use of the long source tube, and the positioning of the microphone, are simply strategies to avoid unwanted reflections; the primary reflected signal is recorded before any back-reflected pulses arrive. The source tube used for impedance measurement in these experiments was considerably longer than that for the bore studies, because the limited memory capacity of our computer imposed an upper limit on the sampling frequency at which we could operate, necessitating a longer recording period to achieve adequate frequency resolution. The longer source tube avoided the unwanted later reflections. Because of the computer's limitations, it was necessary to make separate measurements for impedance and bore that in these experiments could not be readily correlated. With further development, and a computer of greater capacity, computer-aided design could become a very powerful tool. For example, to replace a faulty or missing piece in an antique instrument (even if it were unplayable), one could construct a desired impedance profile, and calculate the bore configuration that would produce it. The converse, starting with the bore and calculating impedance characteristics, would also be possible.

Recently, Louis et al.[10] have described an impulse response system using two microphones (originally suggested by Schroder)[11] that they developed for their studies of the morphology of the pharyngeal cavity in children. The attractive feature of their system is that with two spaced measurement points, secondary reflections can be identified and eliminated in the computation, and therefore a much shorter source tube can be used. A short source tube will be a valuable feature because it will greatly reduce the attenuation of the higher frequencies in the input pulse that we have had to accept, and should improve the resolution

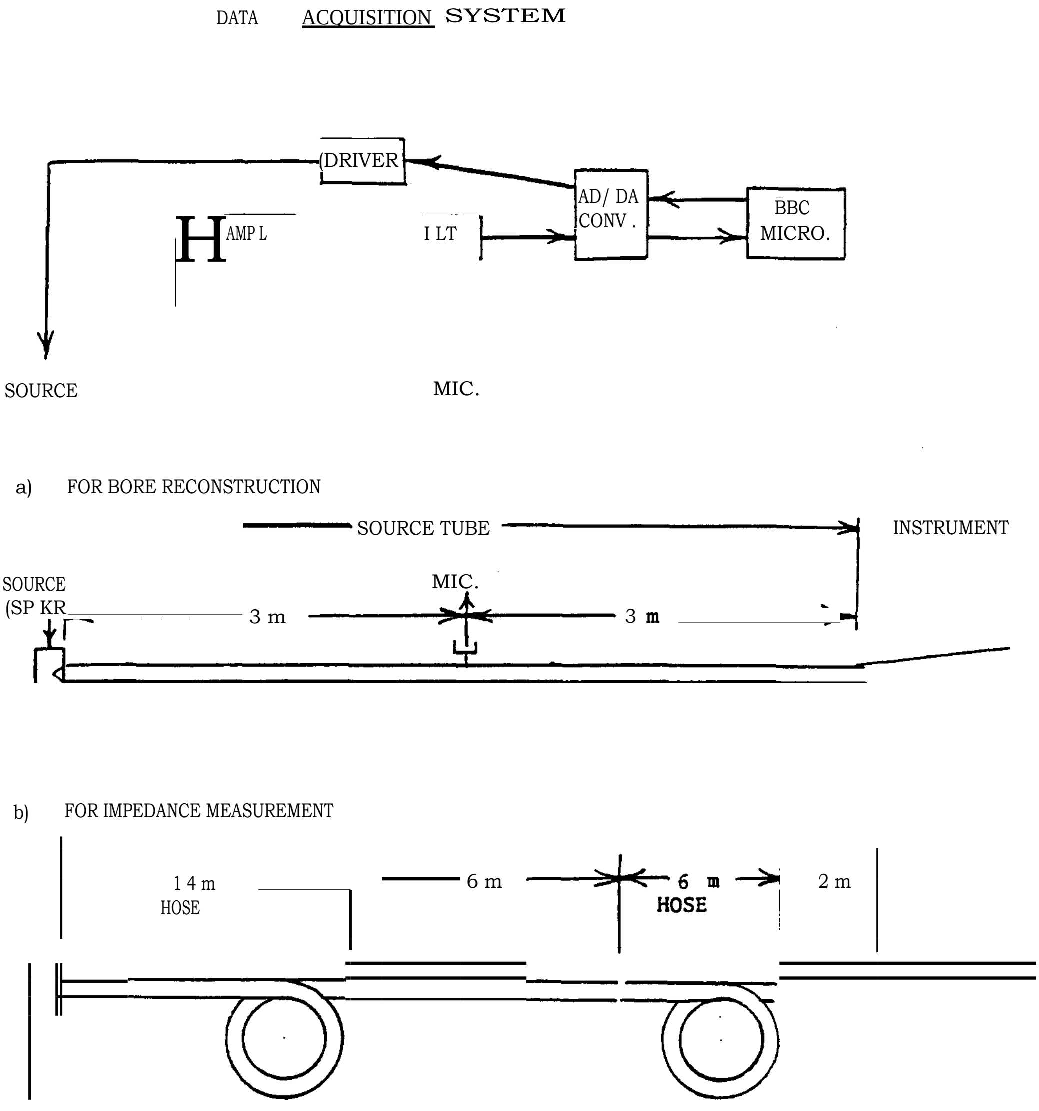



**Figure** 4
The experimental apparatus. See text for details.

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of the bore measurements. The system was developed for area measurements of the upper airway (approximately 20 cm in length), and has not been tested on a structure as long as 200 to 400 cm. It is likely that the computer program will require modification to handle the much greater length of an instrument, but their technique offers promise, and we are looking forward to an opportunity of testing it in this application.

## RESULTS

The following examples are given to illustrate the practical utility of impulse response measurements.

1. Calibration. In order to test the accuracy of the reconstructed bore profile—essential if the method is to be useful in analysis, design and reproduction—a calibration tube was made consisting of a series of joined tube sections of successively increasing known diameters. Figure 5a shows the bore reconstruction of the calibration tube, superimposed on its actual dimensions; Figure 5b is simply an alternative display of the bore reconstruction intended to give a three-dimensional effect. The fit is very satisfactory, except at the abrupt diameter steps where the computation obviously breaks down; this was not deemed important, because in the manufacture of brass instruments, step transitions are generally avoided.

**2. Alphorn.** The alphorn is a conical natural horn, carved of wood, that is usually 3-3.5 m in length. One of us (PAD) is an avocational alp horn builder,[12] and an early goal of our work was to examine the bore and impedance properties of these instruments. Figures 6, 7, & 8 show a comparison of a PAD alphorn to one of Swiss manufacture, by Adolph Oberli of Gstaad.[13] A comparison of the impulse responses in Figure 6 shows the interior of the PAD horn to be considerably rougher, even though the bore profiles in Figure 7 appear to be of comparable quality. (It should be recognized that the calculated bore profile lacks the fine detail provided by the impulse response.) Although a rough bore surface might seem offensive to the instrument maker, it may in fact be a valuable attribute. Smithers, et al., suggest that a major difference between original Baroque trumpets and modem reproductions is that the early trumpets were constructed of tubing rolled from hand-hammered sheets of brass, whereas the modern instruments are formed from machine-made tubing which produces a smoother, more uniform bore.[14] The modern Baroque trumpet is more difficult to play, and its lack of flexibility has led to the practice of placing finger-holes for pitch correction, a practice unheard of in the early instruments.

Figure 7 shows a significant difference in the shapes of the two bore profiles; the PAD horn has a single conical taper, down to the point at which the bell flare starts, while the Oberli horn (which is shorter) is actually two conic sections, with essentially no flare. From discussions with Swiss alphorn makers, we learned that most use the profile with single cone and a flare over the last 0.5-1 m. Ernst Oberli, who continued the family business after his uncle's death, said that, as far as he knew, they were the only ones using the biconical design.

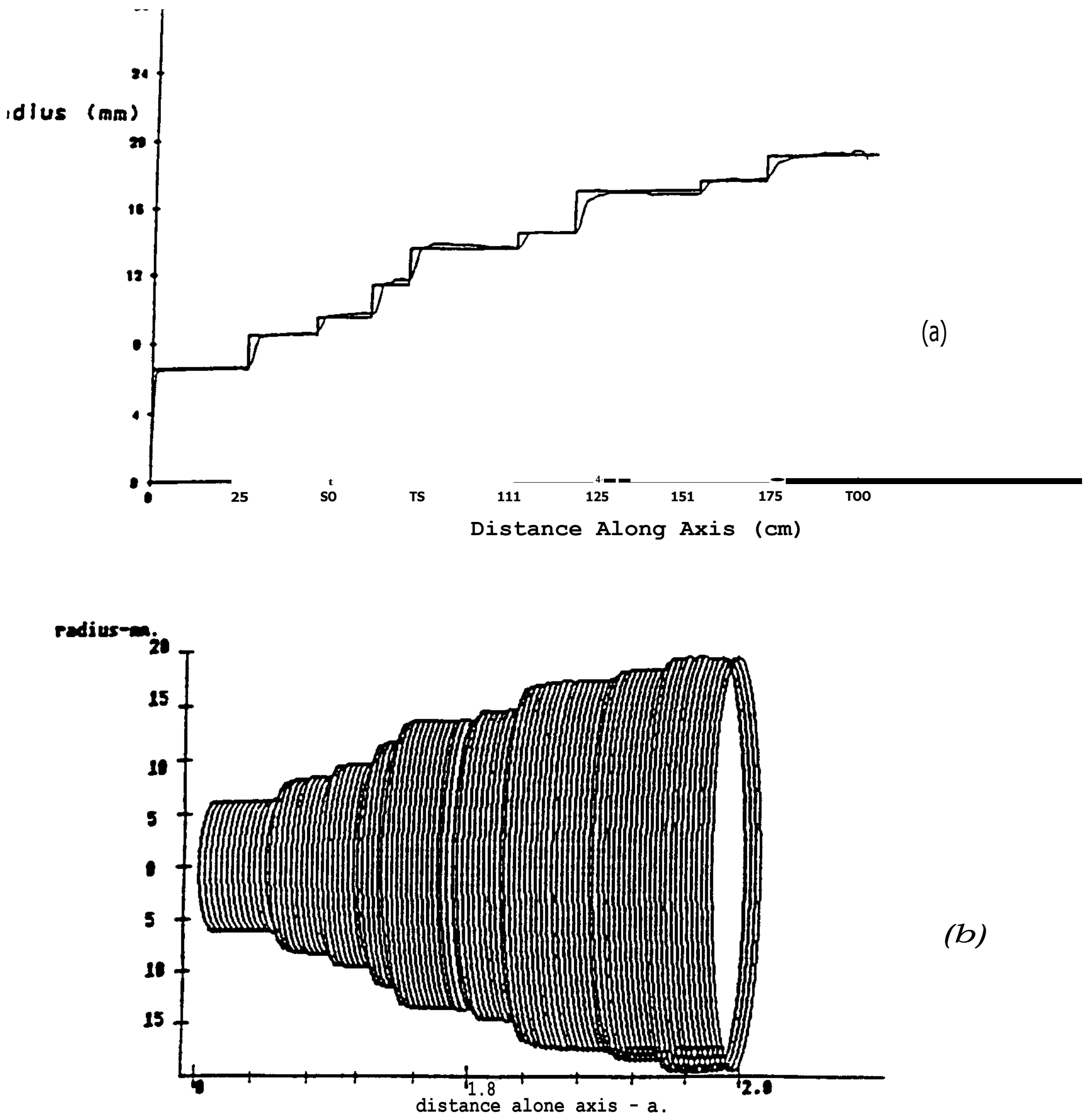



**Figure 5**
Two alternate displays of the bore profile of the calibration tube used to verify the measurements.

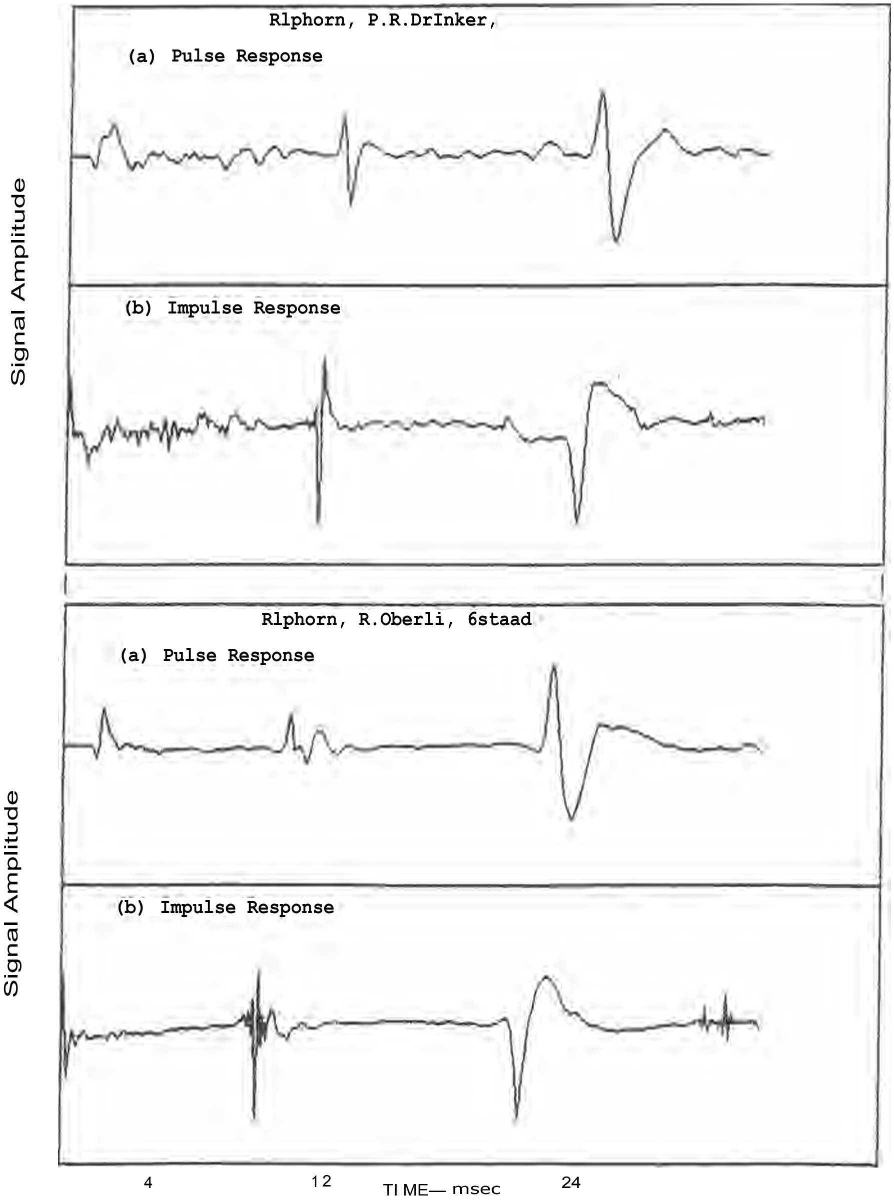
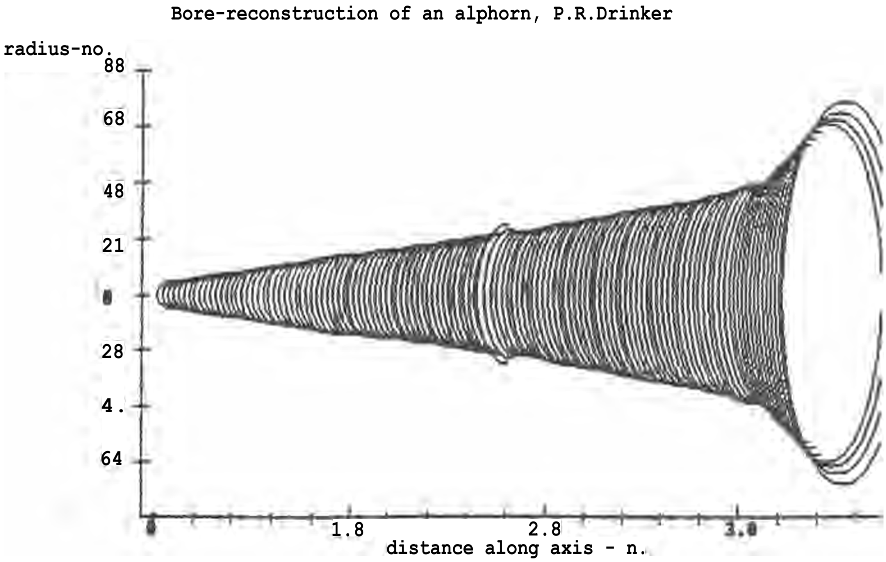



**Figure 6**

Comparison of pulse and impulse responses for two alphorns.



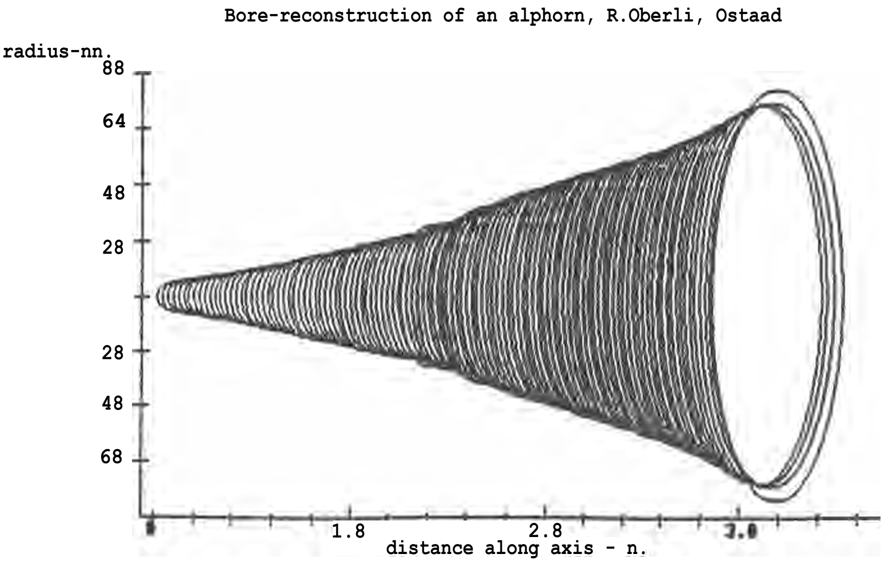




**Figure 7**
Bore profiles for the two alphorns measured in Figure 6.

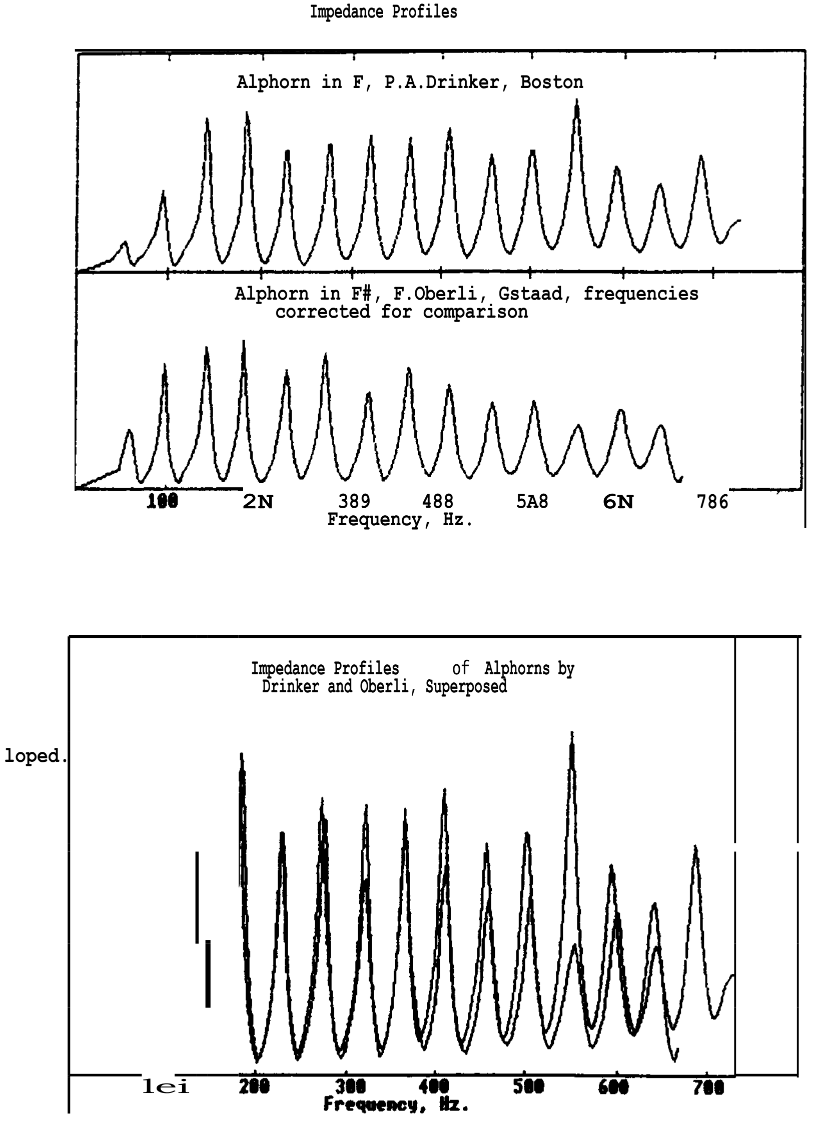



**Figure 8**

Input impedance profiles compared for the instruments in Figure 7.

Judged subjectively, the Oberli horn has great dynamic range, as do two instruments recently made to that design by PAD, and it is tempting to ascribe that feature to the bore profile.

In Figure 8, it should be noted that for the superposition of the impedance profiles, the data for the Oberli horn have been corrected to allow for its higher pitch—approximately one half-step. (It is interesting that the German Swiss horns seem to be based on the Renaissance tuning, A465, whereas those made in French Switzerland are tuned to A440.) The differences in the impedance profiles are consistent with the player's subjective impressions: the Oberli instrument, which has higher peaks at the lowest frequencies, has a somewhat darker sound. More significant is that fact that the PAD horn, although handling well above the second partial, has much less support in the lower frequencies; it is very flat in the second partial, and somewhat weak in the second and third, although the latter sounds well. Based on more recent experience (the instrument shown is PAD's third), it appears that roughness, particularly in the upper section, may adversely affect the lower register, even though the instrument behaves well above the second partial. It might seem tempting to try to correct the problem, but the horn is so pleasing and well behaved in the upper range that it is the instrument of choice for the soprano line in ensemble playing and for solo performance. One leaves well enough alone.

Figure 9 shows the result of an experiment performed with the mouthpiece in the horn, in order to demonstrate its effect. Readers familiar with earlier frequency domain measurements of brass instrument impedance, usually done with mouthpiece in place, will recognize the general form of the lower profile: a gradual rise in peaks with increasing frequency, and then a rather abrupt tailing off. As the superposition shows, there is also shift of the peaks to lower frequencies. The dominant effect of the mouthpiece shown in Figure 9 is the reason these studies were done with the source tube connected directly to the instrument; we were interested in the instruments' properties, which could be obscured by mouthpieces of different design.

3. **Trombone.** Much of the original work at Surrey was done with trombones, and thus it was of interest to us to compare the alphorn and trombone. Figure 10 shows the bore profile of a trombone set to the alphorn pitch (F), in the sixth position (compare Figure 7). Note that for the trombone the diameter changes at the slide are evident. The trombone appears truncated at the bell because the area computation algorithm is based on the assumption of plane waves in a cylindrical conduit, and breaks down in an abrupt expansion where the waves become spherical.

Figure 11, comparing the impedance profiles of the two instruments, shows several striking differences. For the trombone, the greater heights of the first three peaks reflect its strength in the bass register. The noticeable difference in frequency of the first peak of each instrument illustrates the difference in behavior, discussed earlier, of the cylindrical and conical brasses. For the alphorn, all the peaks are nearly equally spaced, whereas for the trombone, the first impedance peak is markedly flat as compared to the higher harmonics. The "fundamental" that one plays on the trombone is known as a privileged tone—it is supported entirely by the higher impedance peaks and is, therefore, in tune. If the true fundamental tone could be played, it would not be pleasing.

Finally, we were surprised that in the peaks above about 350 Hz there are noticeable misalignments, although the two instruments behave similarly, and together they are not dissonant.

4. Serpent. In early 1988 we had the pleasure of working with Christopher Monk (1921-1991), who asked if we could assist him in a difficulty he was having with the reproductions of his 1810 Baudouin serpent—poor intonation on two or three of the notes. Figure 12, the impedance profiles, and Figures 13 & 14, with the bore configurations, show significant differences, and indicated several regions that needed to be reconfigured. (The measurements were performed with the finger-holes taped over, converting it for the tests to a natural horn, rather than a node-stopping instrument.) Figure 15 shows the first reworking of the bore, which was tested and further reworked. After several iterations, the proper bore was achieved, and a well-behaved instrument resulted. Clearly, being able to obtain direct information on the locus of a problem is preferable to cutting and filling empirically and/or intuitively, even if one tries to calculate the loci of the nodes of each harmonic!

A technique developed in these tests bears special mention, because it should be useful to all makers of wooden wind instruments constructed from two longitudinal halves: the iterative tests were performed by joining the two halves with hose clamps, the seams being sealed with tape, so that the instrument could easily be opened, and reworked further. The alternative ofgluing each serpent before the test would not only have been wasteful, it would have been difficult if not impossible to keep track of the changes and their effects.

5. Contrabass serpent. During the spring of 1988, Christopher Monk also asked us to measure the bore profile of the contrabass serpent, affectionately known to serpentophiles as "The Anaconda." This double-sized military-style serpent was, at that rime, the only known instrument of its size. [15]The Anaconda was built in 1840 by two brothers from Yorkshire for use in a marching band. [16]Because it was soon to be sold by its owner, and its ultimate destination was uncertain, it seemed desirable to obtain documentation of the design of this historic instrument. The Anaconda has since been placed in the Edinburgh University Collection of Historic Musical Instruments.

The bore profile of the Anaconda (Figure 16) is markedly different from that of the Baudouin instrument, which is classed as a church serpent. The large bulge at 3.9 m in Figure 16 is a chimney under a key pad, the location of which was confirmed by direct measurement. A rough estimate of the area under the bulge, compared to the actual area of the chimney measured in the plane perpendicular to the instrument axis, showed that the cross-sectional area of the chimney was overestimated in the bore calculation by about 500%. Because the chimney presents an abrupt discontinuity in the bore, the discrepancy is neither surprising nor troublesome, but simply reflects the limitations of the measurement method.

The transitions in the bore from conical to cylindrical, and back to conical, were

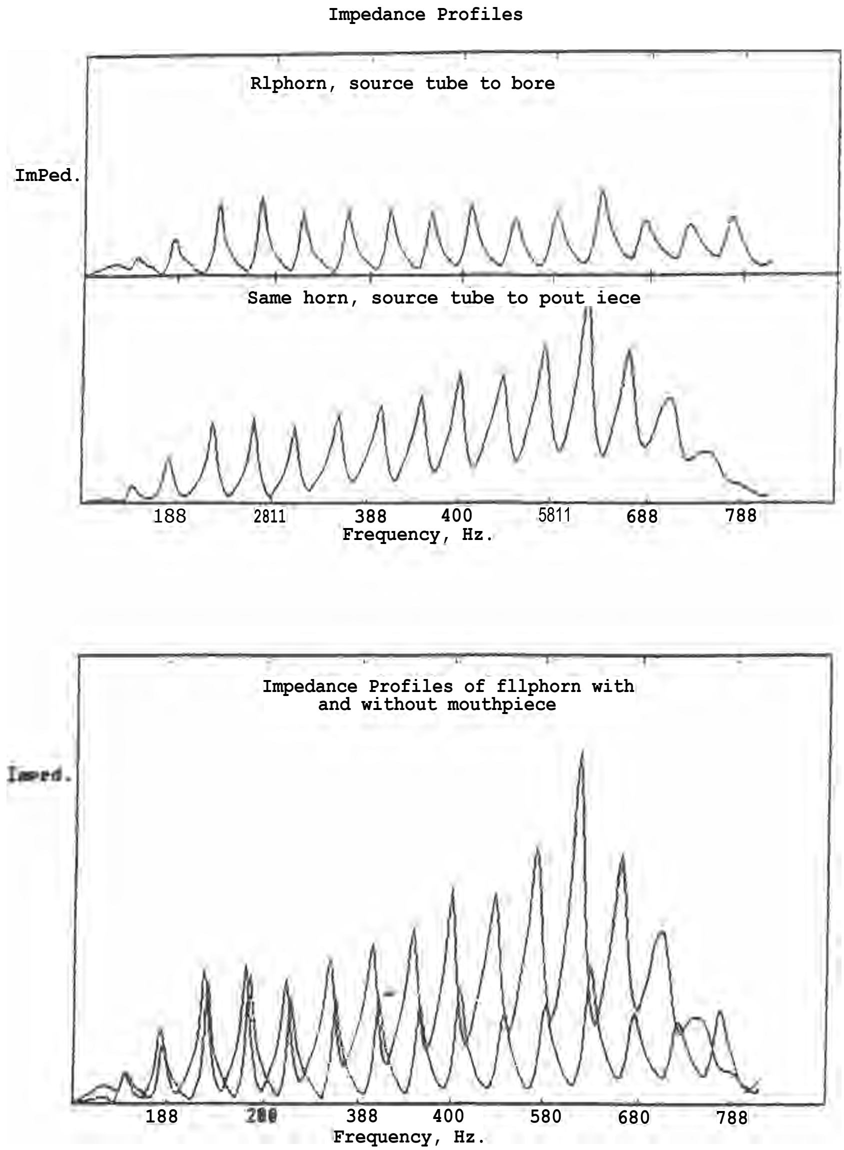



**Figure 9**

Input impedance profiles of the alphorn by PAD, demonstrating the effect of the mouthpiece on the measured characteristics of the instrument.

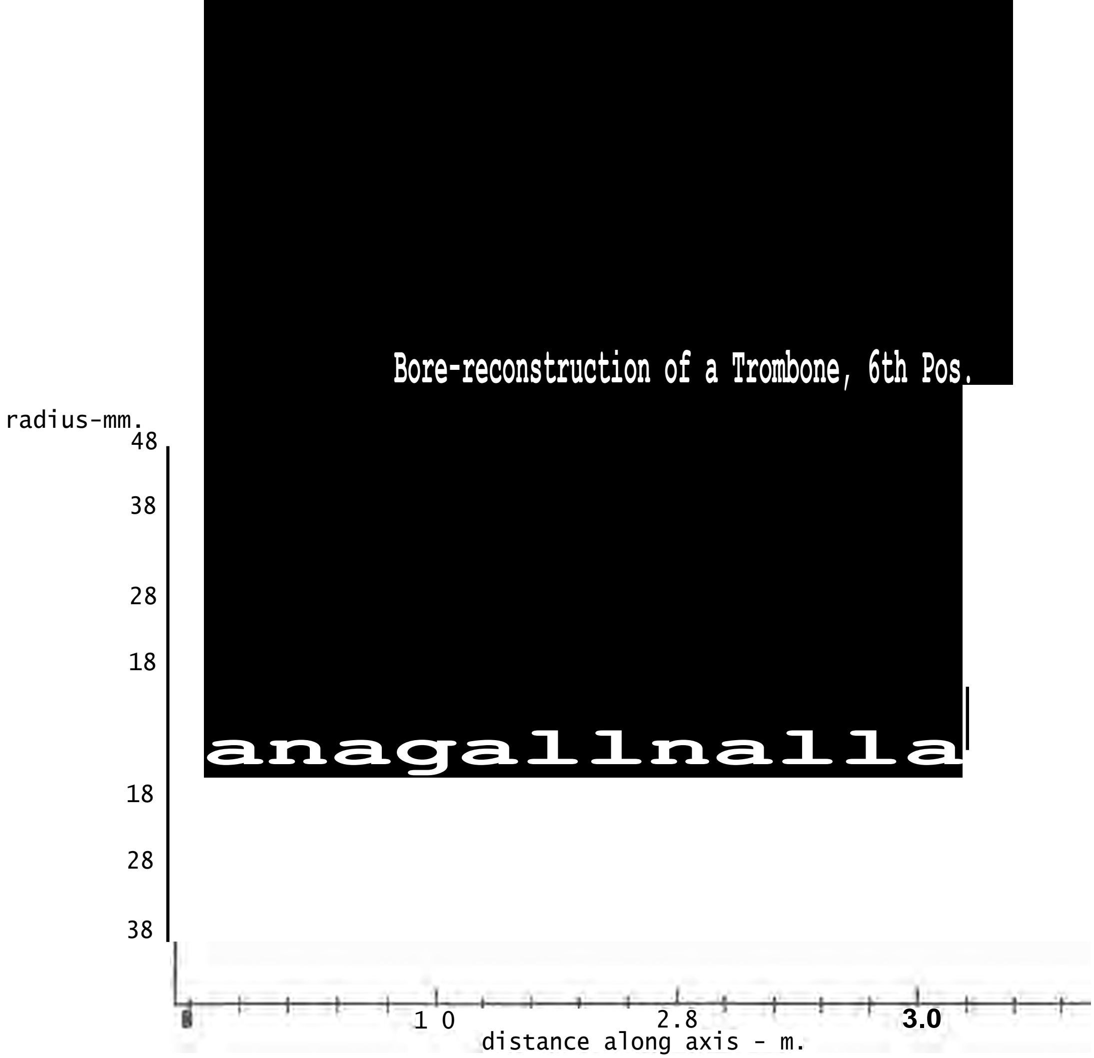



**Figure 10**
Bore profile of a tenor trombone (Boosey and Hawkes Sovereign) in the sixth position (F).

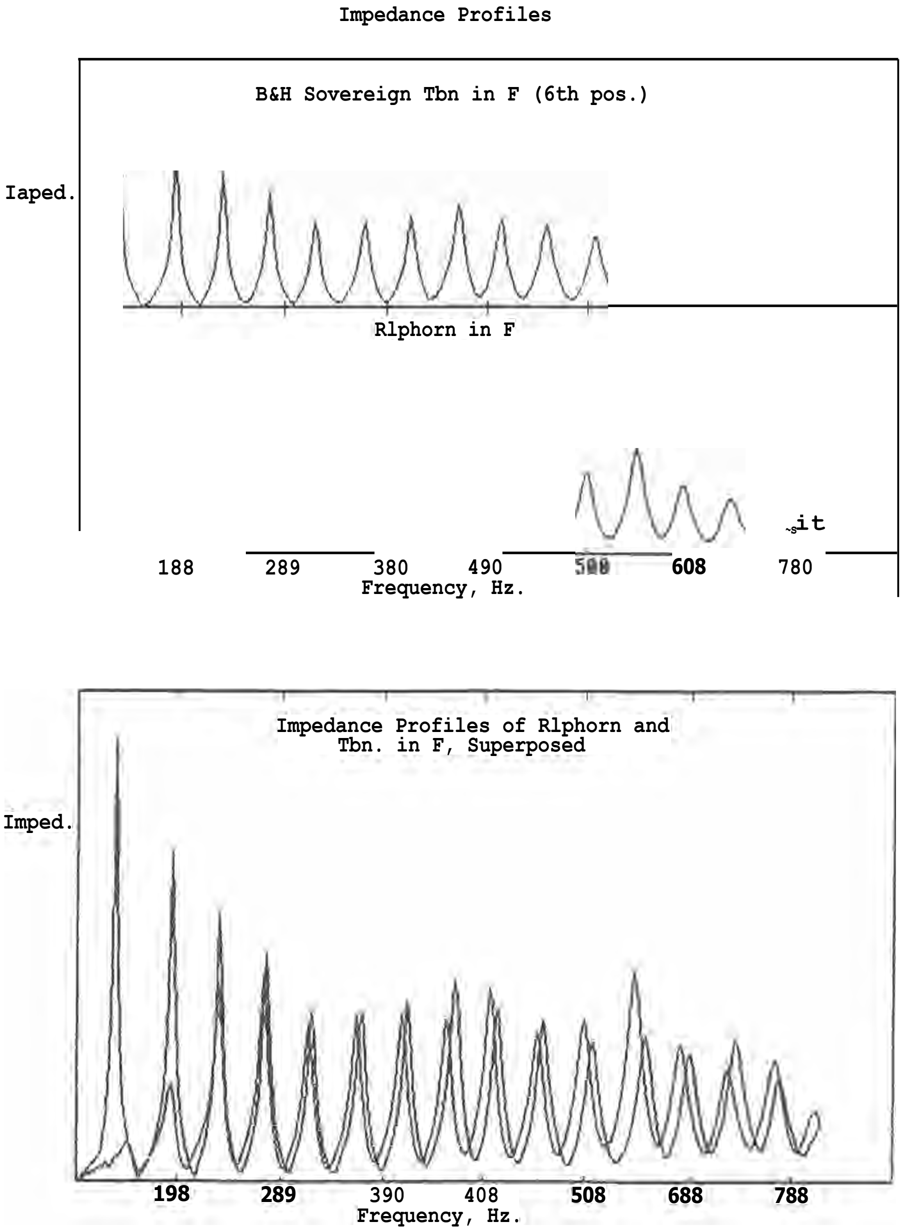



**Figure 11**
Comparison of the input impedance profiles of trombone and alphorn, both in F.

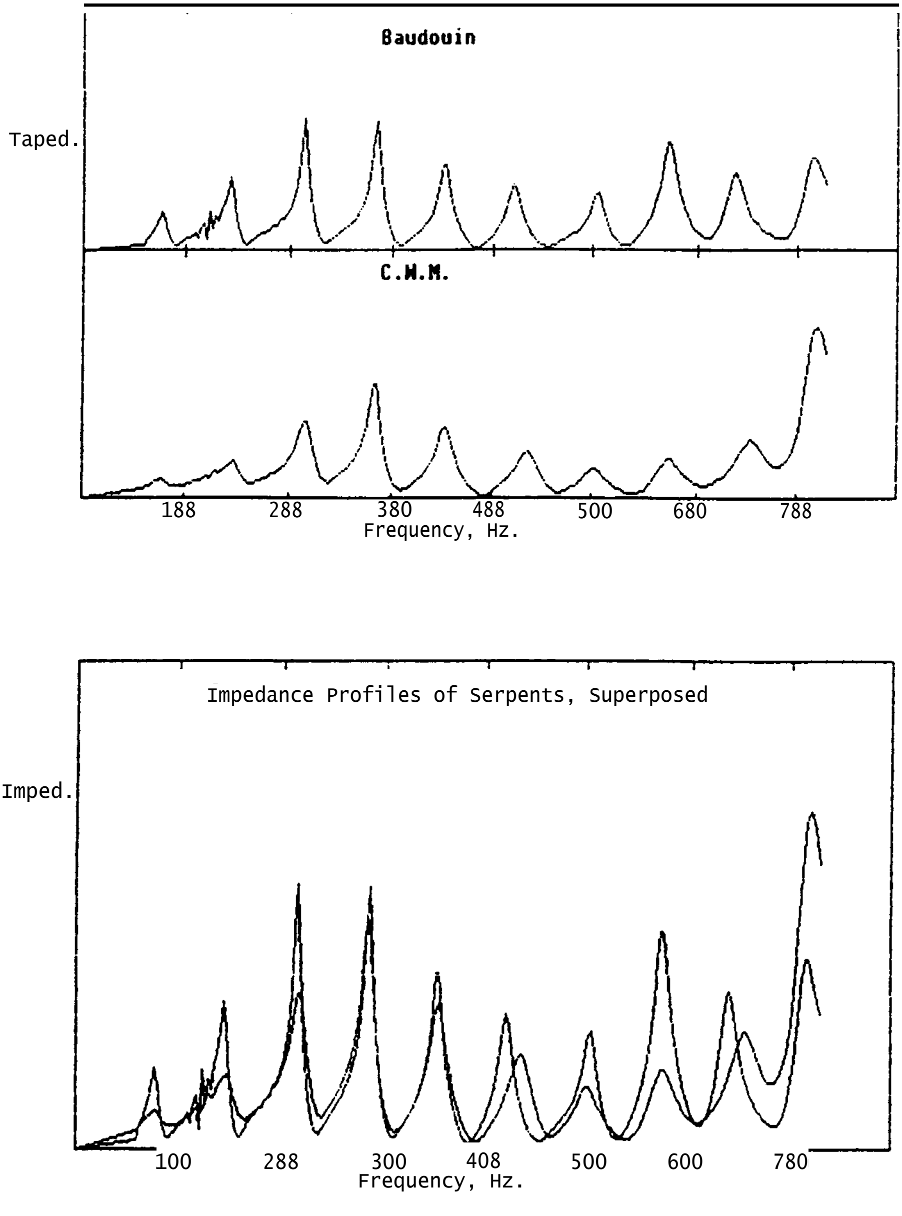



**Figure 12**
Comparison of the input impedance profiles of two serpents, by Baudouin (Paris, 1810) and C.W. Monk, 1987.

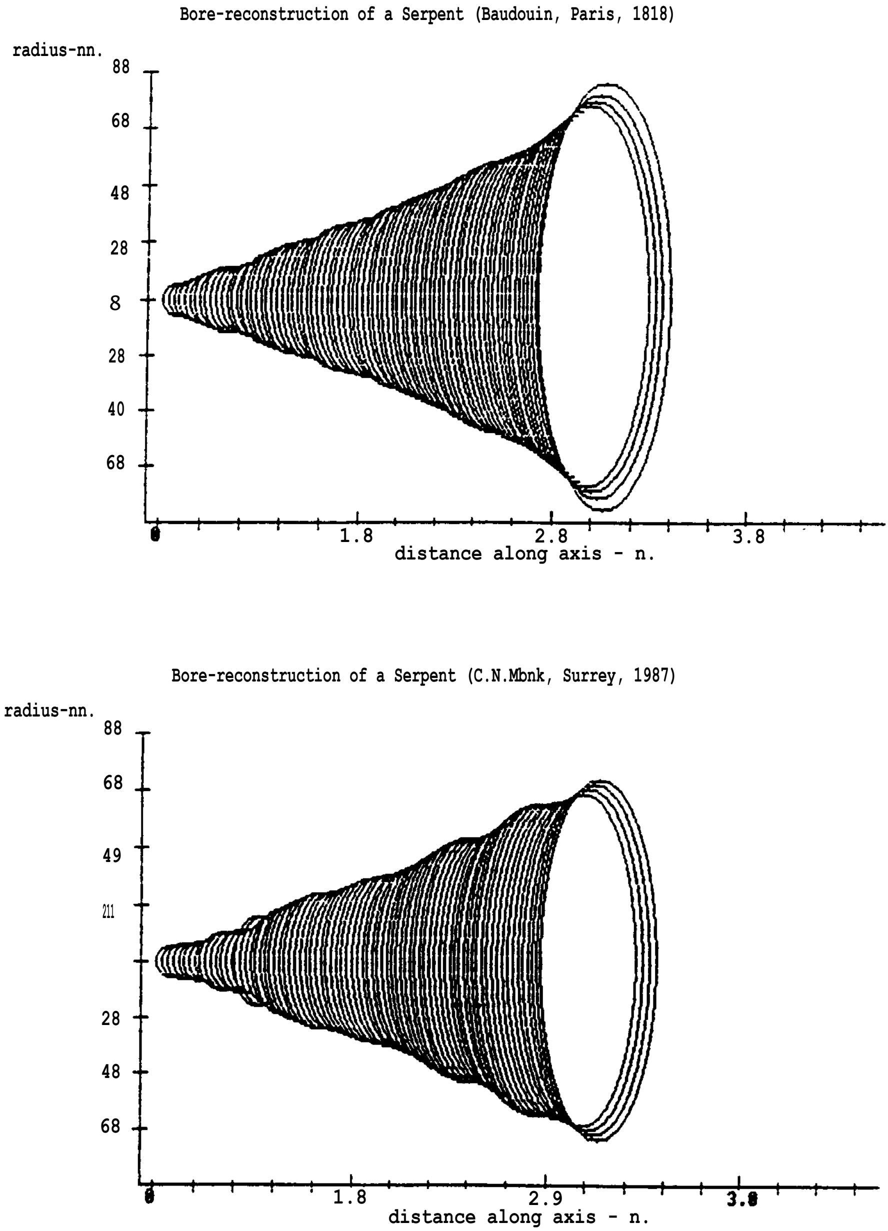



**Figure 13**
Bore profiles of the Baudouin and Monk serpents.

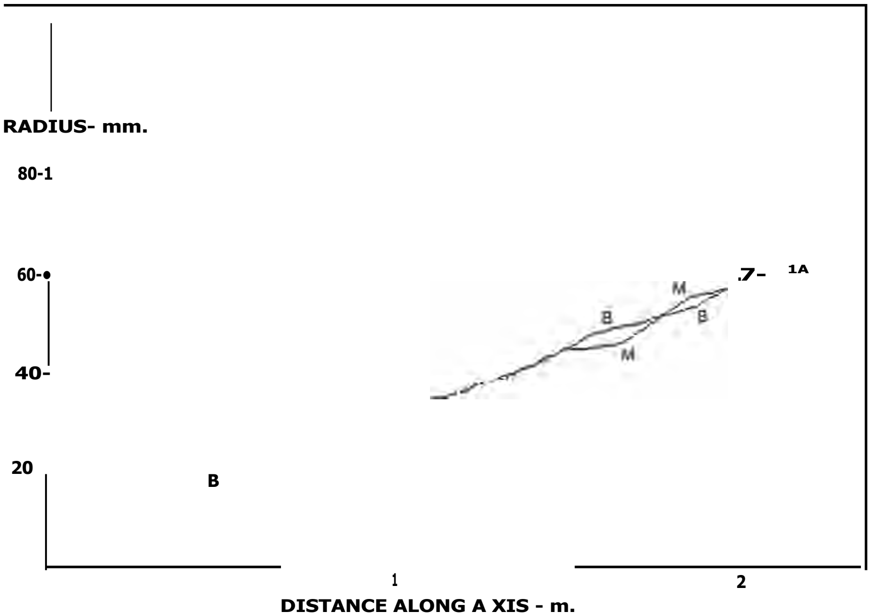



**Figure 14**
Comparison of the bores of the two serpents, Monk, 1987 (M), and Baudouin 1810 (B), used to guide the reworking of the Monk serpent.

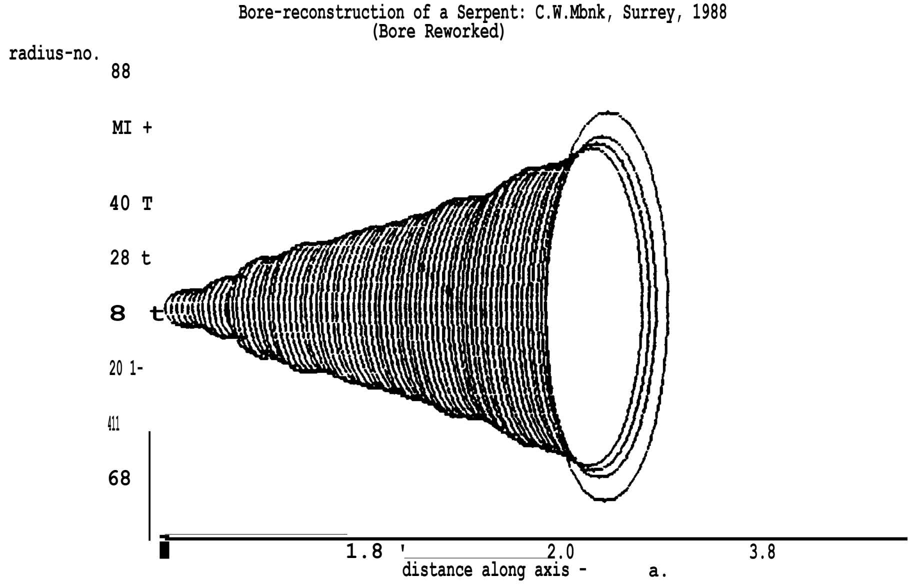
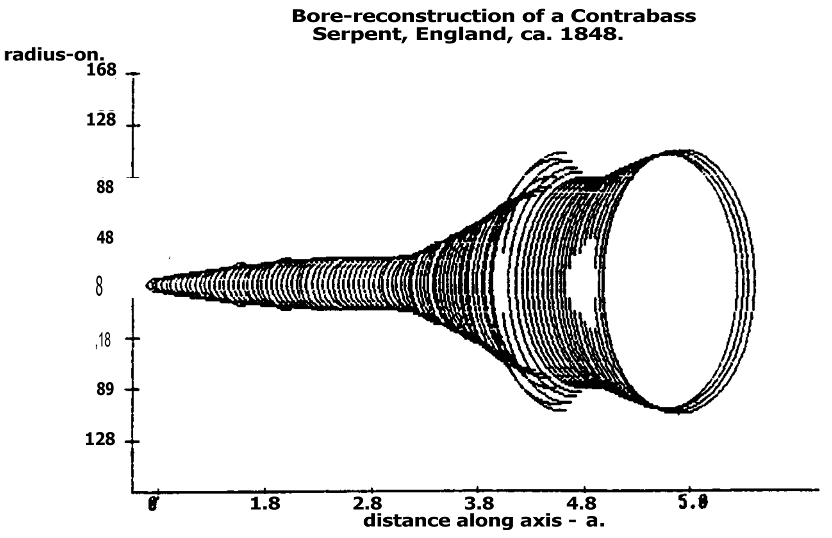



**Figure 15**
The bore of the Monk serpent after the first reworking.



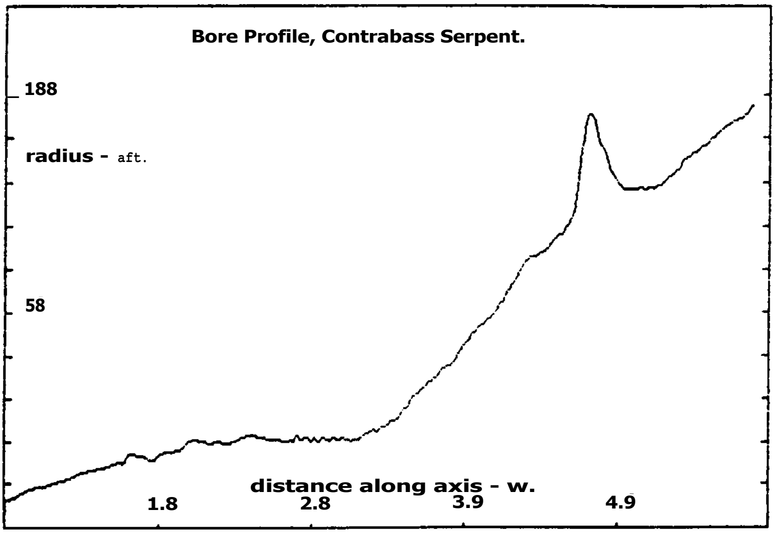




**Figure 16**
Bore profile of the military-style contrabass serpent—"The Anaconda', to its friends. The peculiar bulge at 3.9 m is a large chimney under a keypad. See text for details.

surprising to us, but similar configurations occur in the so-called conical brasses, such as the cornet and baritone horn. It would be interesting to know if the bore profile oldie Anaconda is typical of all military serpents, as we have not had an opportunity to study other instruments of that class.

**6. Impulse response measurements used in quality control for instrument manufacture.** The traditional method of quality testing in the manufacture of *brass* instruments has generally been based on the skills and judgment of a visiting consultant musician, who comes in to test the instruments at the end of a manufacturing run, pronouncing each a pass or a fail. The failures then become a challenge to the manufacturer, who must locate and identify the flaw (e.g., drop of solder, misaligned valve or hairline crack), disassembling the instrument as necessary, and repair it.

In 1987 an impulse response system was purchased by Richard Smith Musical Instruments, Ltd., of London for the measurement of trumpets. To use the system in quality control, it is not necessary to determine the bore profile or impedance characteristics. Rather, the impulse response, showing the distance down the horn of each peak, is all that is required. The impulse response of the prototype instrument (with acceptable playing qualities) is stored on the computer, and is used as the standard against which all other instruments are tested. The locations of any flaws are pinpointed by the positions of differences in the impulse response profiles. Interestingly enough, it does not matter if the impulse response is contaminated by multiple reflections, because one is only interested in differences, and their locations. Thus the source tube can be very short, improving compactness and portability. The only complication is that presented by non-constant temperatures (affecting the velocity of sound) when measurements are made—this may easily be overcome by an adjustment of the computer program controlling the acquisition of data. The sensitivity of these comparative measurements is sufficient to detect a valve misalignment of as little as 0.2 mm. Figurel7 shows the effect on the impulse response of a trumpet, with one valve depressed by varying amounts.

## SUMMARY

We have described a practical method for making noninvasive acoustical measurements of wind instruments, based on the impulse response, that allows computation of both the input impedance profile and the internal bore configuration. In addition, one could start with an impedance profile of an instrument known to be desirable in some way and calculate the bore necessary to produce it without actually handling the original instrument. Conversely, in an antique that cannot be played, the bore profile measured by other means would permit calculation of the impedance characteristics. Although useful in its present form for studying and correcting existing instruments, the method could, with further development, lead to computer-aided design, both for new instruments and for repair and restoration of antique instruments with missing or faulty parts.

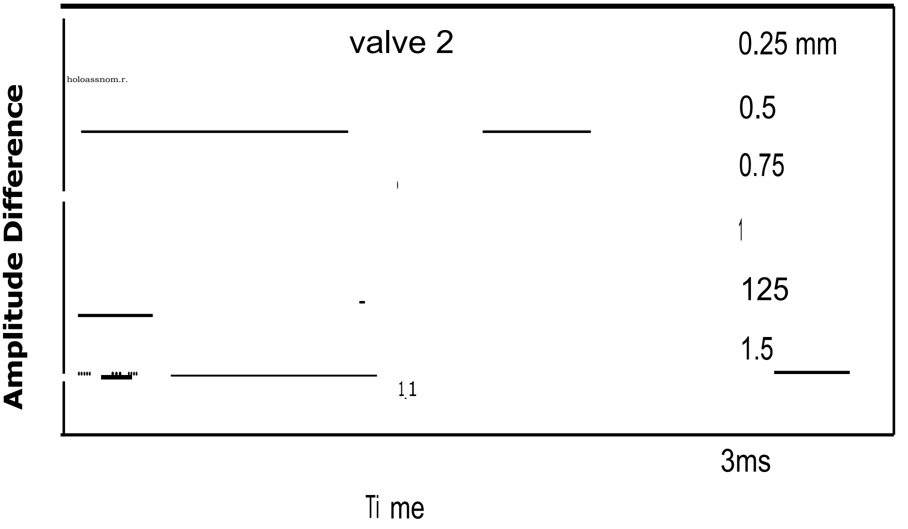



**Figure 17**

The effect of valve misalignment on impulse response in a trumpet,shown for one valve depressed 0.25-1.5 mm. From Watson and Bowsher, "Impulse Measurements on Brass Musical Instruments." Used by permission. The figure was prepared by first determining the impulse response of the trumpet with all valves up, and subtracting that from the impulse responses obtained with a valve depressed by the amounts shown.

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## NOTES

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*About the authors: A six-month sabbatical in John Bowsher's Acoustics Laboratory at the University of Surrey, during 1988, afforded Philip Drinker, a biomedical engineer, amateur hornist and alphorn maker, the opportunity to become immersed in musical acoustics. He retired in 1990 in order to set up a woodworking business and devote more time to playing the horn. John Bowsher is a physicist and bass trombonist, who before his All retirement in 1990 directed the Laboratory of Acoustics at the University of Surrey, Guildford, England*