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## A Special Report:

# Thoroughly Modern Modal Meets Three Old Italian Master Violins

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Although scientific work on violins has been going on for over two centuries, all of the measurements prior to the use of the microphone in the late 1920s are of little use now. Similarly, until about 20 years ago when computer-based modal analysis became a reality, even the details of violin vibration mode shapes so laboriously gathered were little used, although mode frequencies were commonly employed. This incongruity was, in fact, pointed out by John Schelleng [1] after he had published the landmark "The violin as a circuit" paper in 1963 presenting violin octet frequency scaling procedures. He remarked that "Traditionally with tap tones, more recently with electronic excitation, the frequencies and character of resonances have been used for . . . [guidance during violin construction]. *It seems likely that through neglect of their geometric properties we have allowed a source of information to go to waste*" [2] (italics added).

It is in this "geometric" light that a group of scientists, engineers, and violinmakers gathered in mid-September 2006 at the Acoustics Laboratory at East Carolina University (ECU) to analyze three of the finest Old Italian violins (and two contemporary instruments) with the best of modern technologies. The three master violins included two by Antonio Stradivari—the *Titian* (1715) and the *Willemotte* (1734)—and one by Giuseppe Guarneri *del Gesù* (1735) known as the *Plowden*. The two modern violins were made by Joseph Curtin in 2006 and Sam Zygmuntowicz also in 2006. The measurements included three-dimensional vibrations with acoustic analysis over a sphere in an anechoic chamber and computed tomography (CT) scans for density and shape. These efforts culminated in the most traditional, powerful, and conclusive technology: qualitative evaluations by a professional violinist.

## THE VIOCADEAS 3-D EVENT

Why do we care exactly how a violin vibrates? And why are the vibrational mode shapes (hereinafter called modes) so significant? To make an involved scientific story brief: the shape of the vibrations determines how efficiently a violin can radiate sound. It was very difficult to measure the total motion at a point in three dimensions without putting a lot of mass at the measurement point, so the advent of three-dimensional laser scanners a few years ago was a significant event for violin research. The problem was the cost of such systems. Fortunately, Polytec Inc., the only manufacturer of such systems, was as interested in having one of their systems measure some fine Old Italian violins as we were, albeit for different reasons.

Why are such detailed measurements of vibrations so important to scientists and violinmakers? (Other than the obvious: Well, how else are you going to produce sound waves?) Vibrations are entirely determined by our choice of materials and how we construct our violin. Thus vibrations properly analyzed with the right physics can lead right back to material properties. So over a four-day period we applied the most modern vibrations technology to three Old Italian violins so that we could understand in detail how a few choice examples of this most complex, most studied of instruments vibrate and radiate.

The other side of the measurement coin is the computer simulation side. The violin vibrations can be simulated in a computer if a solid model incorporating accurate material density-stiffness properties and an accurate shape can be constructed, which is where the CT scans come into play. CT scans provide the necessary shape and density information, but not the stiffness. Only if we combine our measurements and simulations can we extract important stiffness information for each violin. It is also possible to separate the top and back plates in the solid model to see if their plate mode frequencies agree with separate measurements. Converging these two disparate approaches forms the basis of what we call the VIOCADEAS (VIOlin-Computer-Aided-Design-Engineering-Analysis-System) Project [3].

The picture of the *Titian* (1715) and the *Willemotte* (1734) violins shown in Fig. 1 clearly indicates that Stradivari was still experimenting with violin shape up to his death. Why? Was it in response to the materials? Why would anyone care about a computer model when it is possible to make a violin and test it directly? Because making a violin is a one-way street. You have to decide on a shape to build it, but you cannot un-thin plates, un-varnish the corpus (or that portion that soaks into the wood pores), or

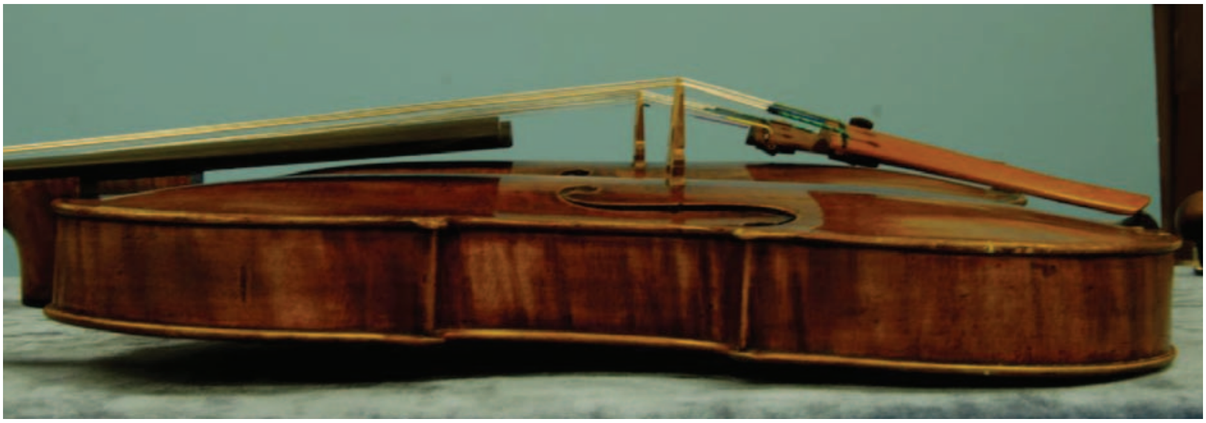


*Figure 1. Side views of the 1715* Titian *(front) and the 1734* Willemotte *violins showing the arching differences in their top plates.*

change the arch after completion. The creation of highly detailed, computer-based solid models that characterize the materials, construction, and response properties of outstanding examples has two important aspects: 1) it archives the fundamental properties of the instrument for posterity and 2) it allows "what-if" experiments: What if the plates are thinned in various ways? What if the soundpost is moved? What if the pattern is lengthened? What if the arching is changed? What if I change my materials? Only by applying both the best modern computer-based vibration analysis and simulation technologies to truly legendary violins will we be able to understand their very essentials: the materials and construction.

## EXPERIMENT

### 3-D Vibrations

Three-dimensional laser scans require three lasers to be able to extract the motion component along three perpendicular axes. In addition, the 3-D system requires that all three laser beams strike the same place as the scan proceeds point-by-point. Figure 2 shows such alignment of the lasers in progress. To do this, the system makes a geometrical scan over the violin surface prior to the scan to generate a three-dimensional surface. Each separate surface requires this scan and an accurate spacing along a particular direction between two points to piece together all the various surface scans into a 3-D model. This makes 3-D scans considerably more time-consuming than a regular 1-D scan. Figure 3 shows a three-dimensional view of the dynamic motion (selected from the animation) of the top plate of the *Plowden* Guarneri *del Gesù* violin.

The 3-D measurements also enabled determination of the out-of-plane and in-plane velocity components, $V_{\perp}$ and $V_{||}$, of the top plates. Generally, it is the out-of-plane (transverse) velocity that produces sound waves. Figure 4—the first of its kind—presents the ratio of these velocity components versus frequency for the top plates of three of the violins (the *Titian*, the *Plowden*, and Joseph Curtin's violin made in 2006).

Is old wood really different from new wood

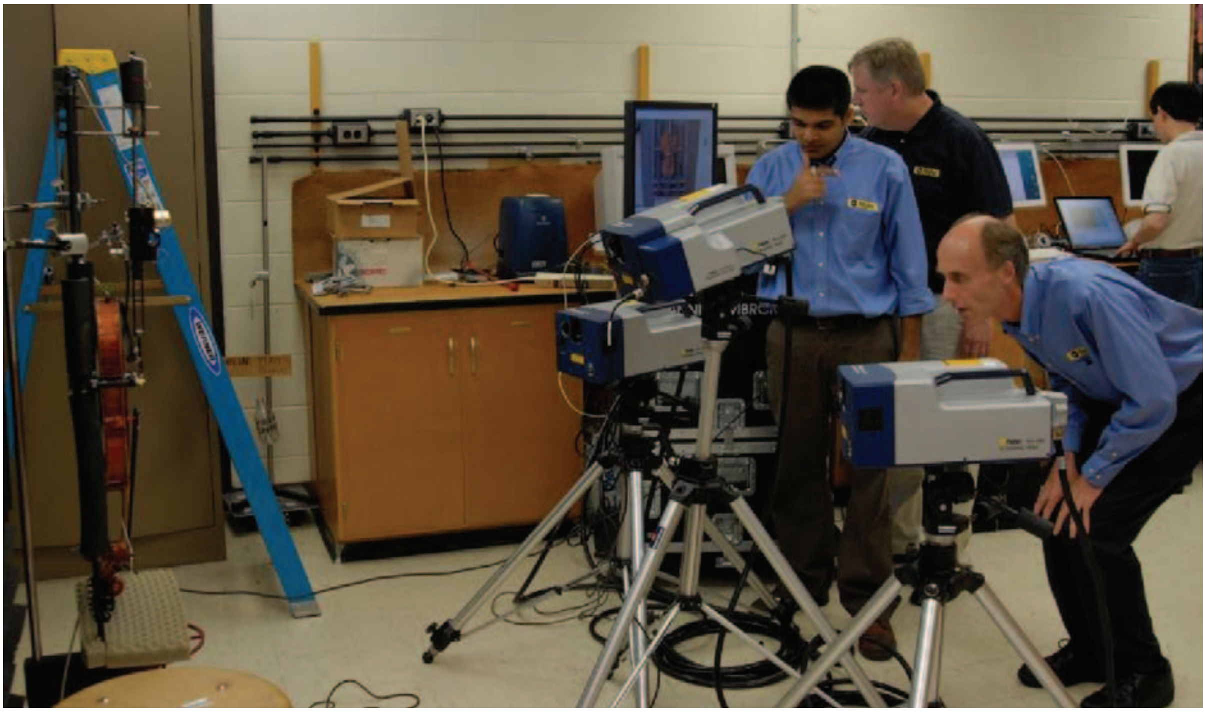
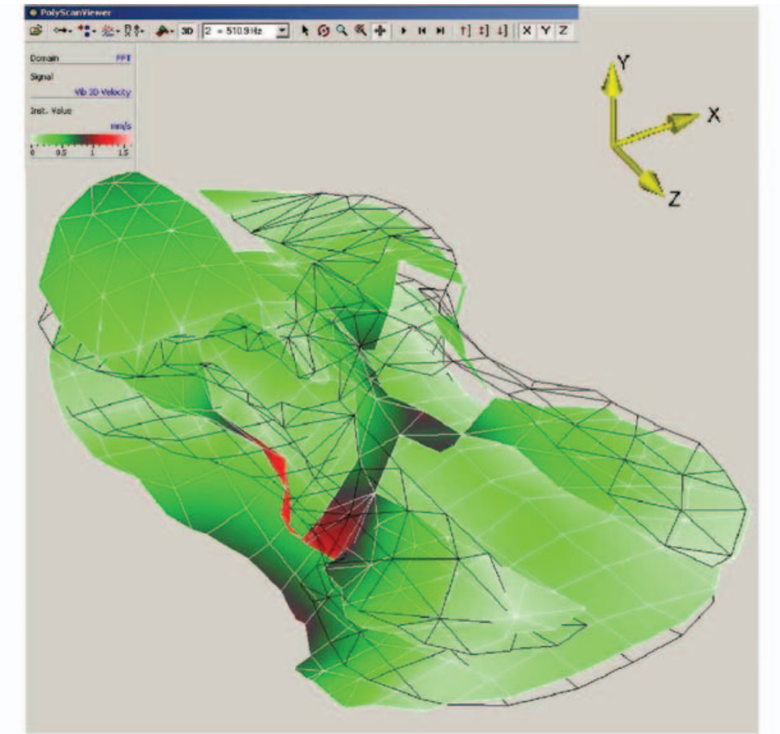


*Figure 2. The Polytec team of (front to back) David Oliver, Vikrant Palan, and John Foley set up the three lasers required for three-dimensional vibration scans in the Acoustics Laboratory of Dr. George Bissinger at East Carolina University. (Photo G. Bissinger.)*



Domain FFT

Signal Vib 3D Velocity

Inst. Value mm/s

*Figure 3. Three-dimensional view of the upper 1st corpus bending mode B1*$^{+}$ *at 511 Hz for the* Plowden *Guarneri* del Gesù *violin. The Polyscan viewer screen shot in frozen 3-D was taken from the animation (wire-frame undeformed grid for reference). This mode is similar to the 1st bending mode in a bar, as the C-bout region is low compared to both ends.*

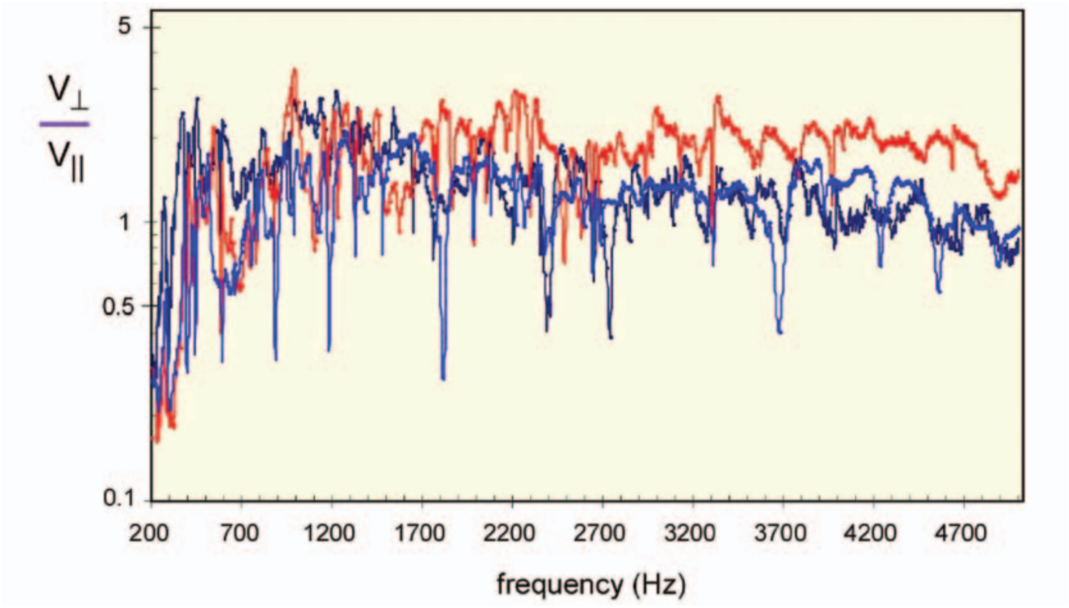


*Figure 4. The ratio of out-of-plane velocity* $V_{\perp}$ *to in-plane velocity* $V_{||}$ *for three violin top plates: the* Titian *Stradivari violin of 1715 (red line); the* Plowden *Guarneri* del Gesù *violin of 1735 (blue line); and Joseph Curtin's violin made in 2006 (black line).*

in terms of its density, stiffness, and damping? That is what all these measurements can help determine. To measure the violin proper(ly) it is necessary to suspend it from light elastics. A violinist holding it will damp the motions strongly, change the way it vibrates, and literally become part of the system being measured. Furthermore, it is best to strike the bridge with a small hammer so as not to attach any mass to the bridge, which can have profound effects on the sound. Why hit the bridge? Because this is where the string energy enters the violin. Finally, measure the motions with a transducer that does not add mass to the violin.

## Overall Sound

Scientifically speaking, it is not possible to work backwards from a desired sound to the mechanical modifications necessary to achieve it, because sound production is the product of two major independent energy filters that act on the string energy as it passes through the bridge into corpus vibrations, and then from vibrations into sound waves. Practically, of course, this is done all the time by experienced people who have learned that a certain mechanical modification will change the sound in a certain way. Such difficulties are inherent in trying to understand violin sound. They are the reasons why experiments that systematically change one variable only are so useful for scientists, even if this is not the way the violin is commonly adjusted by experienced people.

Violins can be quite directional in their radiated sound at high frequencies, so acoustic measurements over a sphere (or hemisphere) are useful for getting some idea about overall averaged sound production. We used the configuration shown in Fig. 5—which features a rotating microphone array combined with a rotating violin support fixture in an anechoic chamber—to measure the sound radiated over the sphere

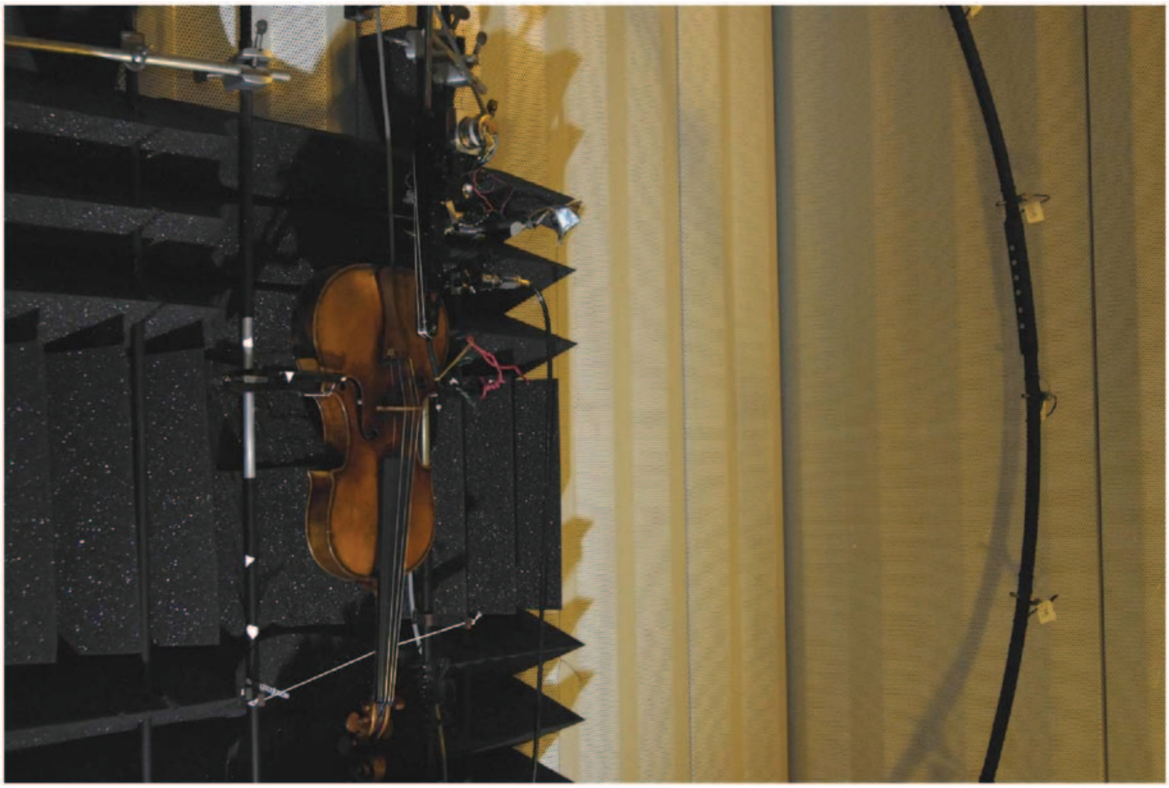


*Figure 5. An Old Italian violin was mounted in the anechoic chamber for acoustic measurements. The same hammer used for tapping the violin bridge for the 3-D vibration measurements was used in the anechoic chamber. The rotating microphone array, combined with a rotating violin support fixture, allowed acoustic scans over the sphere around the violin. (Photo G. Bissinger.)*

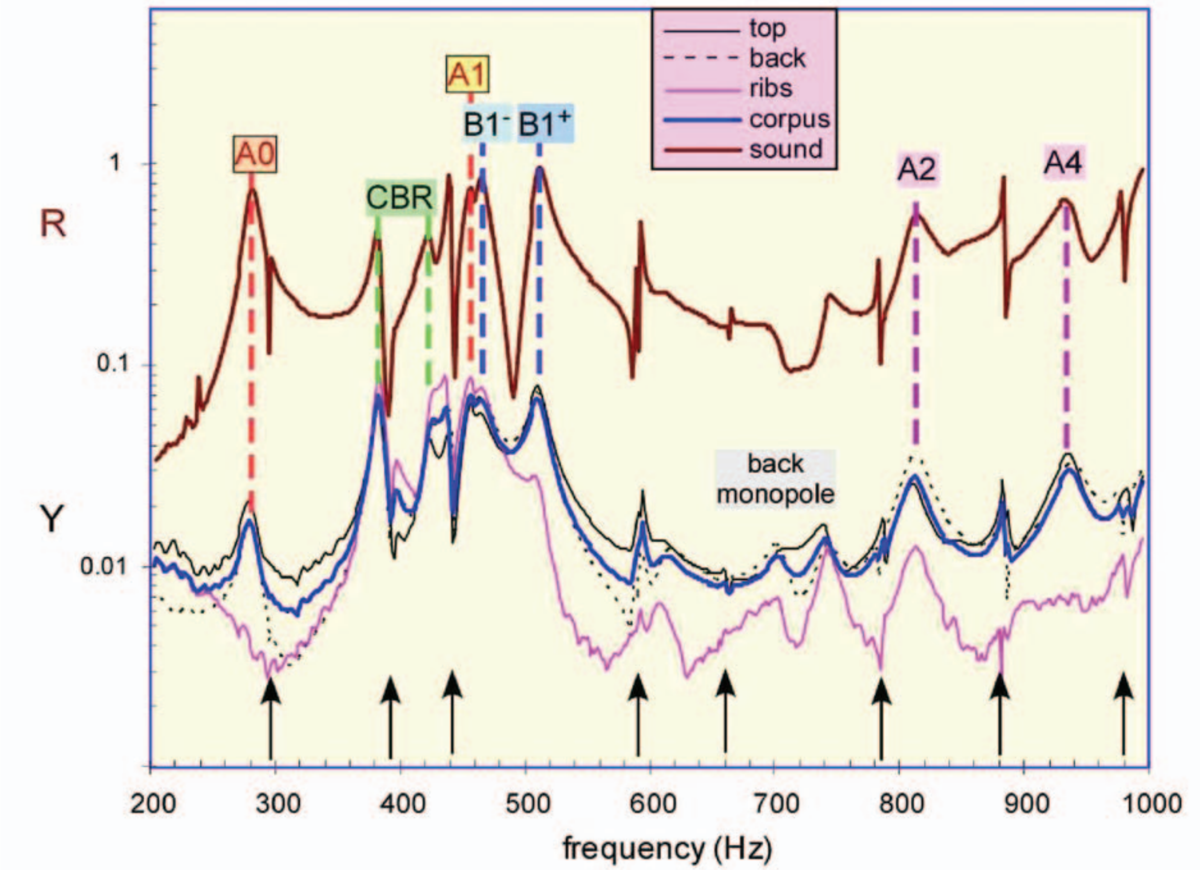


*Figure 6. A "spaghetti" plot overlays the measured radiation (top curve; in Pa/N) and vibration (top, back, ribs all combined into corpus; in m/s/N) of the* Plowden *Guarneri* del Gesù *violin from 200 to 1000 Hz. Below 600 Hz the signature modes identified in all violins are labeled: cavity modes A0 and A1, corpus modes CBR, $B1^-$ and $B1^+$. (Small arrows at the bottom denote string harmonics.)*

around the mounted violin. Combining acoustic measurements with vibration measurements—as in Fig. 6, where vibration and radiation measurements for the *Plowden* are shown overlaid from 200-1000 Hz and mode identifications annotated—gives the added information about which modes radiate best. Note that the scale is logarithmic (and could easily be a decibel scale), which tends to squash the curves, but a common distance between curves does define a common ratio between the curves. Note also the large distance between curves for the A0 mode, indicating that it is sound from the *f*-holes rather than from surface motion that counts.

This particular instrument showed the effect of the cavity modes "talking" very strongly to the corpus, forcing motions that mirror the A0, A1, A2, and A4-cavity mode pressure profiles. Heavy, thick, stiff plates could not respond well to interior pressure variations. For all these cavity modes, the radiation was strong too. As seen in Fig. 6, the A1 mode vibration radiates almost as strongly as the B1 modes, which used to be called the "main wood" resonance before modal analysis showed what the violin really was doing. The presence of motions (and radiation) mirroring the A2 and A4 cavity modes is also noted. (Schelleng [1] disregarded all cavity modes except A0 as being insignificant radiators in his violin octet scaling; the A1 mode totally dominates radiation in the "main wood" region for the largest instrument.)

Finally, the violins were compared by taking the radiativity (pressure measured by microphone per unit force at the bridge) and averaging it over 250-Hz bands. This "smearing" of acoustic response is akin to what happens when the violinist holds the violin and greatly increases

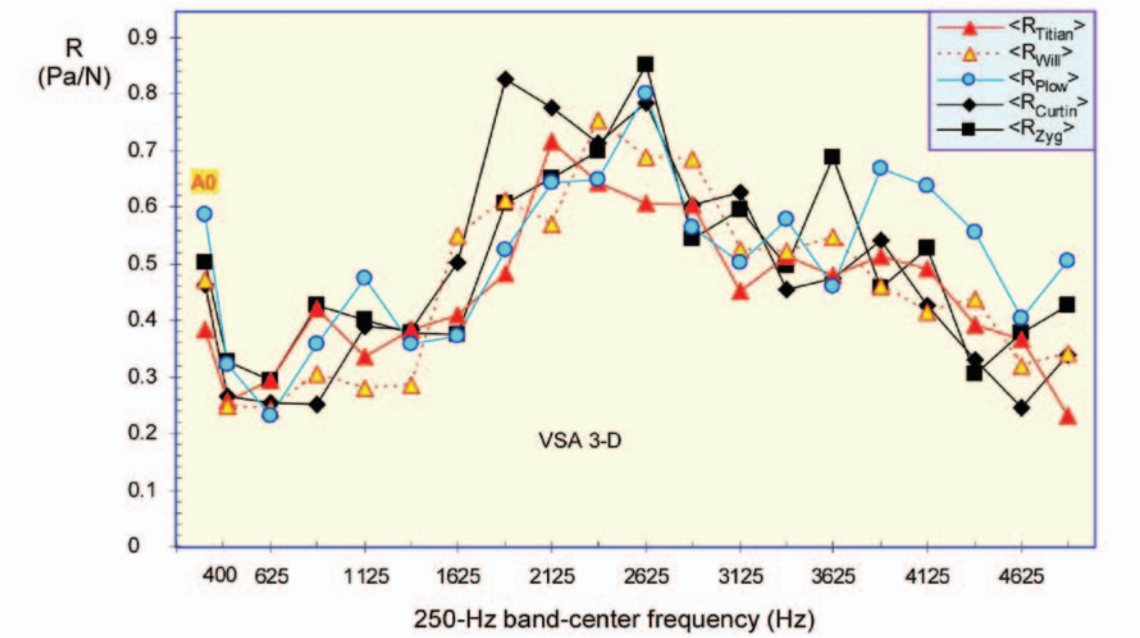


*Figure 7. Comparison of the radiativity R into the top plate hemisphere from all five VIOCADEAS 3-D violins (see legend for key) in the form of band averages over 250-Hz intervals. (Note that A0, which always ranges between 250-300 Hz for a violin with soundpost-in, has been separated out since it is the lowest and certainly predominant radiator below 300 Hz; the next higher band ranges from 300-500 Hz, with center at 400 Hz.)*

the damping. It provides a better gauge of typical relative response since modes overlap so much at higher frequencies. This plot is shown in Fig. 7. Are there any differences between the curves? The short answer is lots! The significantly stronger A0 mode of the *Plowden* relative to the *Titian* stands out, while the violin by Zygmuntowicz overall has the strongest response. The myriad of details even in this simplified set of curves certainly is not amenable to easy, quick analysis.

Figure 7 indicates that the A0 mode is strongest for the *Plowden* and weakest for the *Titian*, and this is reflected also in the A0-mode strength relative to the rest of the band-averaged response. This is probably part of the reason that the violinist described the tone of the *Plowden* as "milky, like honey," while the *Titian* was described as having a "brighter, thinner" sound. The *Titian* also appeared to have a more consistent and faster falloff above 4 kHz.

## CT Scans

Fundamental density and shape information comes from the CT scans. Density and shape plus wood stiffness properties are the crucial ingredients in creating a reliable solid model of the violin with the computer. The CT scans allow looking inside the violin and inside each wood piece. Putting the information from many slices together makes it possible to recreate the shape of the violin and its parts quite accurately.

The CT measurements of the three Old Italian violins (the *Willemotte*, the *Plowden*, and the *Titian*) were made at the same time by mounting them three high, as shown in Fig. 8. Displays of the CT scans for these instruments are shown in Figs. 9 and 10. Three-dimensional reconstructions are also shown in Fig. 10.

## Qualitative Evaluations

It was a morning to treasure. After three days of hectic activity, after the Polytec crew had packed up and left the previous afternoon, we sat down in Bissinger's living room to listen to the violins being played by Ara Gregorian, a member of the ECU School of Music faculty and a graduate of the Juilliard School (Fig. 11). The instruments were set in a row on a loveseat, and Ara picked them up and played and talked about the sound

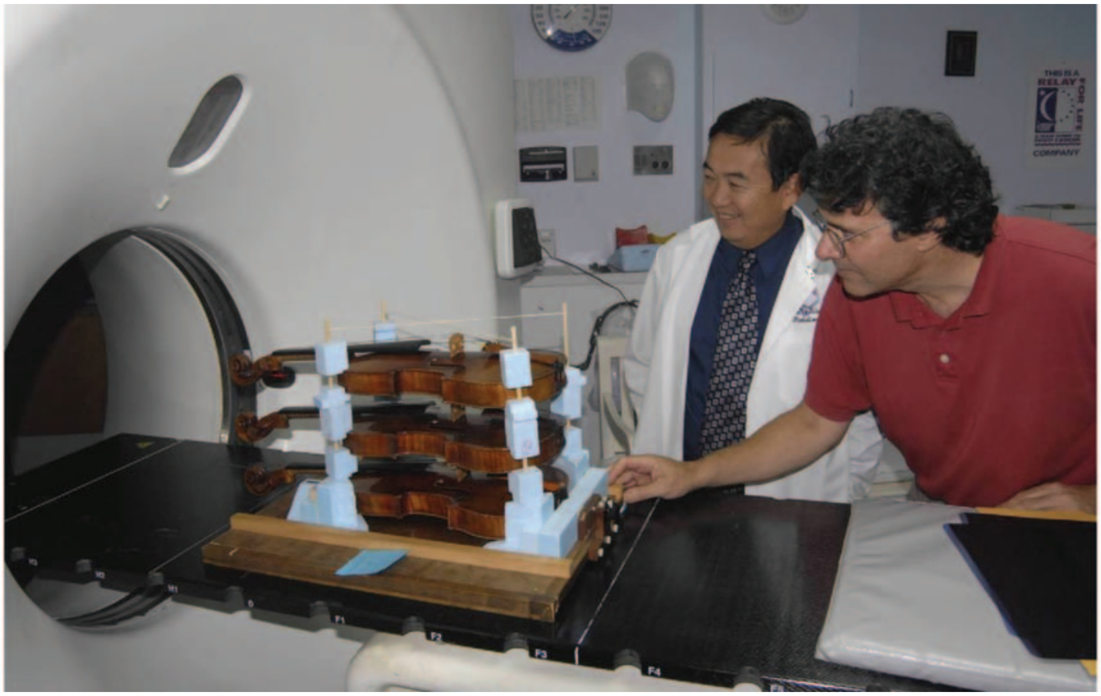


*Figure 8. The Old Italian violins were stacked three high (bottom to top: the* Titian, *the* Plowden, *and the* Willemotte*) for the CT scan measurements. The scans were performed by Dr. Claudio Sibata, head of Medical Physics staff at the Leo Jenkins Cancer Center, with the assistance of Sam Zygmuntowicz.*

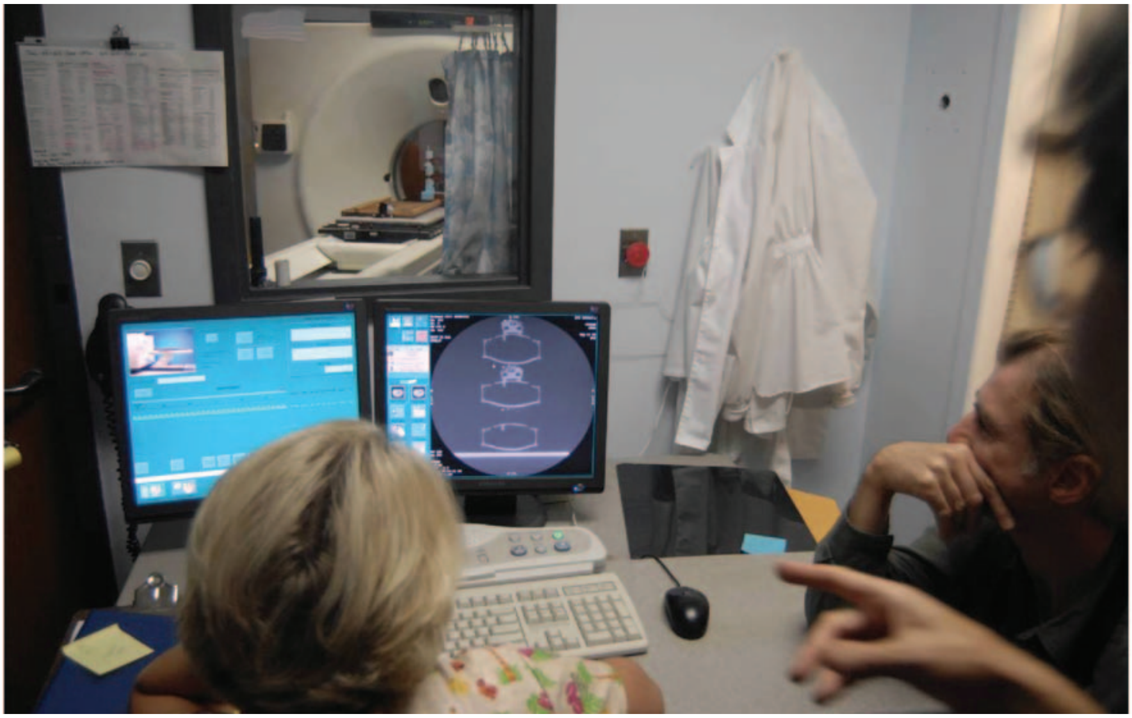


*Figure 9. The three stacked Old Italian violins had their innards examined using Computed Tomography (CT). The density changes between the woods and air are recreated as screen brightness differences that appear as a slice through the violin. (Photo G. Bissinger.)*

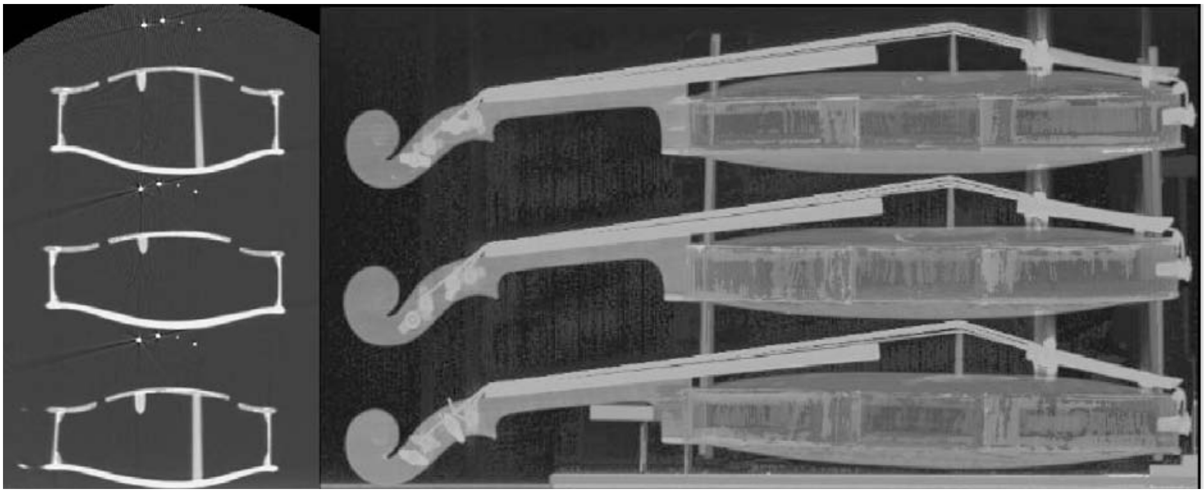


*Figure 10. Left: CT scan slice 455 showing the* Willemotte *(top), the* Plowden *(middle), and the* Titian *(bottom). The brightness scale reads directly in density with proper software. Right: 3-D view reconstruction of these three violins.*

*Figure 11. Ara Gregorian plays one of the Old Italian violins in the Bissinger living room at the end of the four-day 3-D event.*

*Figure 12. After everything was finished, a somewhat exhausted VIOCADEAS 3-D group sat for a group picture. Front, left to right: George Bissinger (holding the* Titian*), Danial Rowe, and Fan Tao; back, left to right: Joe Regh, Joseph Curtin, and Sam Zygmuntowicz.*

and feel of these fine violins. (Ara was the violinist who had evaluated all the violins in the previous VIOCADEAS analysis.) The authors were in quite a mellow mood, ready to lean back and just listen to the *raison d'être* for doing all this in the first place (Fig. 12).

While all the data have been taken and the VIOCADEAS 3-D Project has drifted sweetly into our memories, the data analysis is still proceeding. Like the classical piece "Mon fin est mon commencement" (My end is my beginning) by Marin Marais (French composer and viol player, 1656-1728), getting to the end of the four days means we will have just begun.

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