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Acoustical analysis of stringed instruments without touch

Heidi von Rüden(1) and Anton Schlesinger(2)

(1)State Institute for Music Research of the Prussian Cultural Heritage Foundation, Germany, vRueden@sim.spk-berlin.de
(2)theapro, daberto + kollegen planungsgesellschaft mbh, Germany, a.schlesinger@theapro.de

Abstract

At an abstracted level, the stringed instrument consists of a box with a neck and fastened strings. The design of the resonator determines the sound. Therefore, the acoustic measurement of instruments plays a prime role for functional analysis and digital archiving. In this contribution an acoustical, contact-free measurement method for quantifying the transfer function of guitars is presented. The method assesses the sounding body and its periphery by means of a standard acoustical impulse response measurement (AIR). As a test signal a logarithmic sweep is employed that offers a high signal to noise ratio and the ability to separate potential harmonic distortion of the electronic signal chain from the impulse response of the instrument. The measurement is compared to the hammer probe, which is the current gold standard method for measuring the transfer functions of sounding bodies and the periphery of stringed instruments.

This contribution summarizes an ongoing investigation. Prospectively, AIR is an ideal tool for functional analysis, long term monitoring of instruments as well as quality control. Instruments are not subjected to mechanical stress and do not have to be prepared for play. The sonification of the impulse response allows for aural assessment and may complement the description of stringed instruments in archives.

Keywords: Measurement, stringed instruments

1 INTRODUCTION

In the museum the meaning of an instrument changes from a tool of the musician to an historical artefact. Due to the functionality a musical instrument has always a technical background. A museum not only shows the external appearance of an instrument, further aspects are important to understand how an instrument works, as for example the material, the construction and its manufacturing process.

The requirement for an acoustical measurement technique arose at the museum of musical instruments, which is part of the Stiftung Preussischer Kulturbesitz (Prussian Cultural Heritage Foundation). It is located in Berlin at the State Institute for Music Research (SIM). The museum collects instruments of the European classical music tradition from the 16th to the 21th century. The conservators are in charge of nearly 3200 instruments.

For the staff of the restoration laboratories the preservation of the object is the principal goal. The ICOM code of ethics for museums sets minimum professional standards and encourages the recognition of values shared by the international museum community. *Museums have the duty to acquire, preserve and promote their collections as a contribution to safeguarding the natural, cultural and scientific heritage* [1]. Therefore, a protective environment with a careful monitoring and documentation is essential and part of the museum's work.

Although the museum comprises a vast collection of instruments, only few instruments are in a playable condition. Often the physical maintenance of an instrument as a whole is more important than studying the sound of it. The restoration of an instrument requires different concepts. Heavily used and old materials need special care. Despite due diligence, the new stringing of a lute can still lead to irreversible damages if a joint between soundboard and shell opens or the bridge tears off because of high string tension. The documentation of the acoustical context of an object is therefore being considered more and more often as an alternative to executing sound measurements or recordings with strung instruments. However, fundamental research questions on sound qualities cannot be answered in this way.

Rare but popular with visitors are concert projects and recordings with a limited duration of playing time on instruments of the collection. Concerts with plucked instruments of the museum collection are even more seldom. Guides of the museum generally work with copies of bowed and plucked stringed instruments.

As regards the acoustical description of a string instrument in an archive, the resonances are of prime importance. Among which, the Helmholtz resonance (HR) strongly determines the sound of an instrument, namely

the sound volume and sonority. It depends on three parameters, the volume, the size of the sound hole and the stiffness of sound board. The larger the volume, the deeper the resonance. Furthermore, the band width (Q-factor) of the HR is influenced by the material density and flexibility of the sides of the instrument's body. There are further acoustic features in the transfer function that are characteristic to certain models of stringed instruments [2]. The transfer functions are generally captured by the hammer probe method. The excitation by hammer is however problematic for historical instruments, because the applied force can cause damage. Nevertheless, the hammer method is a reliable measuring method for instrument makers in order to monitor acoustic conditions during the construction process. In recent years, the importance of this method has been recognized more and more in the context of organology.
In this contribution, an alternative acoustical probing method for string instruments is presented. The method is purely acoustical, hence contact free and therefore much less destructive than the hammer method. To many people dealing with instruments, the method is already known from the excitation of the HR by singing into the sound hole. In this contribution, this testing method is systemized as an acoustical impulse response method (AIR) and general questions for retrieving reliable results are discussed. This contribution starts with the presentation of the AIR method. Thereafter, the method is validated and discussed.

ACOUSTIC IMPULSE RESPONSE (AIR) METHOD

The proposed method is based on two room impulse response measurements, one with the string instrument present and one without. Subsequently, the room is eliminated by numerical deconvolution, which results in the impulse response of the sounding body of the string instrument alone.
The logarithmic sweep was applied as the measurement signal. This excitation signal for measuring the impulse response is characterized by a high and frequency independent signal-to-noise ratio (SNR) and removes harmonic distortion of the signal chain [3]. In order to get the impulse response of the string instrument h_i, two signals are recorded in the time domain[1]

$$y_\mathrm{r} = s * h_\mathrm{r} \tag{1}$$

$$y_\mathrm{r,i} = s * h_\mathrm{r,i} \tag{2}$$

with y_r, $y_\mathrm{r,i}$, s, h_r and $h_\mathrm{r,i}$ being the convolutional product of the room and s, the convolutional product of the room, the instrument and s, the logarithmic sweep (swept sine), the impulse response of the room and the confounded impulse response of the room and the instrument, respectively. Because $h_\mathrm{r,i} = h_\mathrm{i} * h_\mathrm{r}$ and the possibility of forming the inverse of the logarithmic sweep, the impulse response of the instrument can be retrieved by deconvolving the room impulse response from the confounded impulse response

$$h_\mathrm{i} = h_\mathrm{r,i} * h_\mathrm{r}^{-1} \tag{3}$$

Which is equivalent to

$$h_\mathrm{i} = y_\mathrm{r,i} * y_\mathrm{r}^{-1} \tag{4}$$

Because this calculation of h_i contains a collateral dirac (from the deconvolution process of the room) followed or superimposed by the smaller impulse response of the instrument, h_i needs further preconditioning before analysis. In this work, the dirac was simply subtracted by

$$\hat{h}_\mathrm{i} = h_\mathrm{i} - y_\mathrm{r} * y_\mathrm{r}^{-1} \tag{5}$$

[1] The index t for indicating the time domain representation is dropped in the following formulae for the sake of brevity.

The numerical implementation of the deconvolution process needs a stabilization constant. This constant however amplifies low frequencies noise in the resulting impulse response. As a countermeasure, a high pass filter with a very low cutoff frequency was applied to $\hat{h}_{\mathrm{i}}$ in this work.

VALIDATION

1.1 Comparision with the hammer probe

The measurements were taken at two different locations, the University of Applied Sciences / Department of Musical Instrument Technology in Markneukirchen and the State Institute for Music Research of the Prussian Cultural Heritage Foundation / Department III: Acoustics and Music Technology and Department I: Museum of Musical Instruments in Berlin. The climatic conditions on both places were similar.[2] Subject of the investigation were two newly built guitars with different design made by the first author. A modern concert guitar and the replica of a 19th century terz guitar. The sound quality and the artistic crafted work of the research objects are comparable with guitars of the museum in Berlin. The instruments allow further investigations on timbral features because they are playable. The material of the classical guitar is very conventional. The back is strongly arched. It has three ribs. The soundboard is made from spruce with fine growth rings with a thickness of 2.2 to 2.5 mm. The guitar has seven fan struts, the outer ones reach down through the crosswise bar into the sound hole area. The shape of the strutting is asymmetrically, the treble side is made stiffer than the bass side. The terz guitar is made from maple and spruce with an inner mold like a violin. The back has four cross ribs, equally divided. The soundboard has also four cross ribs, two above and two underneath the sound hole. The part of the bridge is reinforced. The neck fits with a screw to the body. The fingerboard holds these two parts together. The sound qualities of these two guitars differ highly.

Figure 1. Classical guitar (left) and terz guitar (right) used in the comparison between the AIR method and the hammer probe.

At the Department of Musical Instrument Technology the measurement was taken in a small studio on a table. The guitar was supported in laying position by foam material underneath the area of the end block and the neck block of the body. The strings were damped by hand. The accelerometer was fastened with wax on the soundboard of the guitar, at the point of 6 cm (6,5 cm/ terz guitar) from the bridge-saddle E-string (G-string/

[2]Due to the ethical standards according to ICOM, with very high safety requirements, we choose instruments of private property and not from a museum collection for this project. The transport of the guitars was not air-conditioned. The temperature and relative humidity in the locations in Markneukirchen and Berlin were recorded: In Markneukirchen the relative humidity was 53% at 19,5°C, the premises in Berlin is air conditioned with a humidity of 55% at 21°C

terz guitar) straight to the end of the body. The piezo sensor (model: Piezotronics Model 352B10 with a sensitivity of 10.04 mV/g or 1.024 mV/m/s2) and the hammer (model: PCB 086 B01) were connected to the FFT Analyzer (Ono Sokki CF-7200 FFT Analyzer). The knocking was executed in the middle on the saddle of the bridge by hand and averaged. A coherence function served as a quality criterion of the measurement accuracy.
The presented method AIR was executed in the anechoic room of the SIM for the sake of a controlled environment, predominantly for a reduced acoustical background level. All six surfaces of the room are covered with wedge shaped absorbers. The floor consists of walkable netting with meshes of 60 mm. The room has a volume of around 50 cubic metres. The guitar was placed on the floor, supported by foam material (200 x 80 x 20 mm) on the upper and lower part of the body. The guitars lie very stable in this position. The contact time to the foam material was limited. The object had no other physical contact to the interior or the equipment. Each measurement lasted about 20 min. The guitars were placed on the floor and the omnidirectional microphone was fixed at a height of 1.90 m, perpendicularly above the bridges. The position of the applied omnidirectional loudspeaker was at the opposite corner of the room. The distance between the loudspeaker and the microphone was 3.50 m. The distance between the middle of the guitar body and the loudspeaker was 3.83 m. The strings were damped by polyester fleece.
The applied swept sine had a length of 8 s and a sampling frequency of 48 kHz. During the measurement, the maximum Z-weighted sound pressure level was at 105.4 dB at the microphone. In each measurement, the sweep recording was executed three times and averaged in order to improve the signal to noise ratio (SNR). The recording chain obeyed the requirements for room acoustic measurements in auditoria [4] and consisted of an omnidirectional measurement microphone type NTI M2230 (sensitivity 43.3 mV/Pa), a digital audio interface type RME Fireface UFX II, an amplifier type PA 1000 and a dodecahedron speaker type QSAM QS12. The measurements were executed with Matlab, The Mathworks.
For calculating the power spectrum, the impulse response was analysed with the periodogram technique with a Hamming window, favouring the suppression of the leakage effect rather than an exact representation of the signal's power in the frequency domain.
In order to test the robustness of the AIR method, the locations of sender and receiver were altered. The quasi-omni source, the applied dodecahedron loudspeaker, was turned in steps of 0, 30, 60 and 90 degrees, as it is known that these speakers are not fully omnidirectional. An effect that is pronounced in an anechoic room. As a second variation, the position of the instrument with respect to the microphone and the loudspeaker was changed in three steps on an axis from 0 m (perpendicular below the microphone), to 0,55 m and 1 m. In order to safe time, only four impulse responses for angular rotations of the dodecahedron loudspeaker (0, 30, 60 and 90 degree) were measured to capture the impulse response of the room alone. Figure 2, (a) depicts the comparison for the classical guitar and 2, (b) for the terz guitar. Note, a constant of 150 dB was added to the power spectrum of the AIR method in order to facilitate the comparison. As can be seen the power spectrum of both methods resemble each other in the regions of the acoustic resonances. At higher frequencies there is generally no congruency observed. The resonances lie at around 100 and 200 Hz for the concert guitar and roughly at 180 Hz for the terz guitar. The positioning of sender and receiver leads to a standard deviation of approximately a maximum of 10 dB. However, due to a measurement mistake, the impulse responses of the room (without the instrument, Eq. 1) were acquired for slightly different angular positions of the loudspeaker and a longer sweep signal. Therefore, it was not possible to calculate the impulse response with Eq. 4 but with Eq. 3, which reduces the SNR. Additionally, the mismatch between the angular positions in the impulse response of the room and the confounded impulse response may result into the observed standard deviation.

1.2 Analysis of microphone distance to the sound hole

In 2016 multiple guitars of the SIM collection where measured with the AIR method. As compared to the setup presented above, each measurement was executed with two microphones, a cardioid microphone (type Beyerdynamic TG I53c) directed to the sound hole at an distance of 34 cm and an omni directional microphone (type Beyerdynamic MM1) at a distance of 110 cm to the sound hole. The setup of sender and receiver

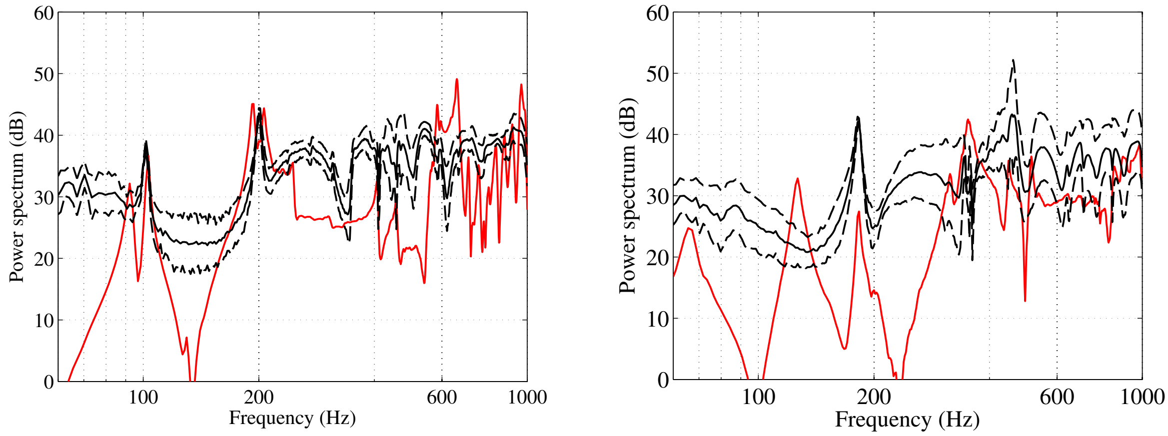

Figure 2. Power spectrum of the classical guitar (left) and the terz guitar (right) measured with the hammer probe (red) and the AIR method (black). The solid lines represent the mean, the dashed lines the mean $\pm$ standard deviation.

remained unchanged between measurements of $y_{\mathrm{r,i}}$ and y_{r}. The data is used to study the effect of microphone distance and the usage of y and h in the deconvolution process.
Figure 3 shows the transfer functions of the 1890's Guitar of Salvador Ibanez in Table 1. As can be seen, applying h instead of y reduces the sound power and likewise the signal to noise ratio. Moreover, the fine structure at higher frequencies appears to be lost when applying Eq. 3.
Increasing the distance to 110 cm reduces the signal to noise ratio considerably, to the extent that it becomes difficult to find the resonances of the guitars. Note that the self noise of the Beyerdynamic MM1 is higher than of the microphone NTI M2230, which was employed in the measurement of the previous section with a distance of $\geq$ 1.9 m to the sound hole.
Based on the 34 cm cardioid pickup and the deconvolution process using the microphone signal y, the guitars of Table 1 are analysed in Fig. 3, (b) and 4. The power spectrum allows for a direct readability of the HRs. The lower part of Figure 4 reveals further information on the timbral characteristics, as for example modulation characteristics.

DISCUSSION

From the conducted experiments, the following conclusion can be drawn. The AIR method cannot replace the hammer probe. Primarily because the AIR method does not capture mechanical oscillations. AIR measures the acoustical response of the sounding body. Therefore, the AIR method can assess the HR, harmonics and overtones.
A typical example of insight is derived from the power spectrum acquired with the hammer probe in Fig. 2, (a), which was not possible with the AIR method alone. The neck of the concert guitar is reinforced with two carbon rods. These bars (330 x 12 x 5mm) are not visible in photos. They were glued into two slots under the fingerboard into the cedro wood. They stiffen the neck. As a result, only little energy of the sound is lost to neck vibrations. This is an interpretation for the fairly high resonance of the neck vibration, just shortly before the HR resonance.
The AIR method as executed here, owns methodological weaknesses. First, the recorded sound power of the instrument is low. Decreasing the distance of the measurement location has shown to improve the sound power and more importantly the SNR. The distance of 1.9 m has been chosen in this analysis to measure as far as possible in the far field of the sounding bodies. It is likely that a compromise has to be defined here. Also,

Item	Instrument	Material	Soundboard area [cm^2]	string length [mm]	Helmholtz res. (Hz)
a	Guitar Salvador Ibanez Valencia around 1890	spruce, mahogany, rosewood, cedro	1035	640	120 Hz
b	Guitar Salvador Ibanez Valencia around 1900	spruce, rosewood, cedro	1328	655	90 Hz
c	Guitar Karl Höfer GmbH Bubenreuth 1992	spruce, rosewood	1402	650	100 Hz
d	Guitar Walter J. Vogt, Horb-Mühlen 1983	spruce, rosewood, ebony, mahogany	1415	652	100 Hz
e	Lute (Ud) unknown maker Turkey before 1955	pinewood, walnut, tortoise shell	—	569	130 Hz

Table 1. Guitars of the collection of the State Institute for Music Research.

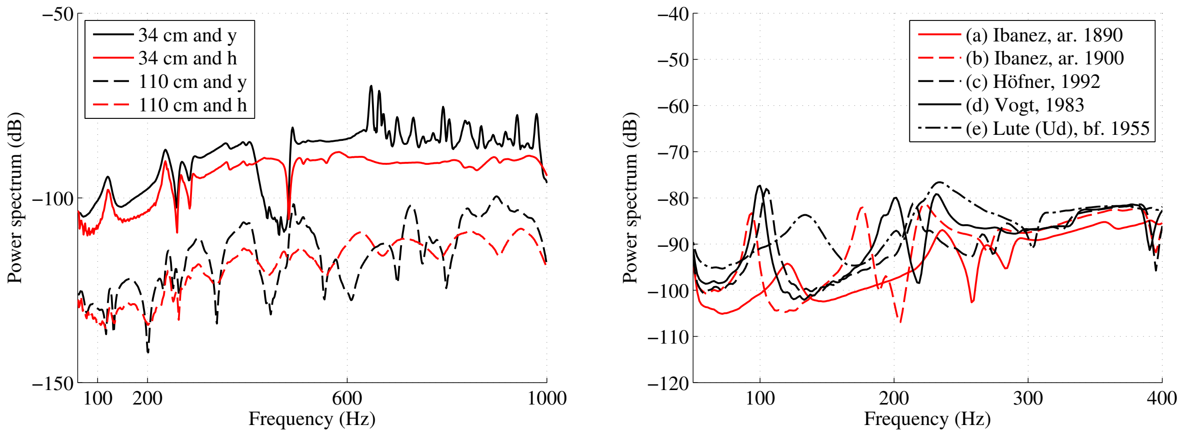

Figure 3. Left: Power spectrum of the guitar of Salvador Ibanez from 1890 measured with the AIR method at difference distances from the sound hole and based on the deconvolution of the recorded signals or the pre-processed impulse responses. Right: Comparison of the acoustic resonances of the guitars in Table 1.

the hammer method measures at a specific point (at the point of 6 cm from the bridge-saddle E-string) and does therefore not give a fully comprehensive image of the spectral behaviour of the guitar. The method is however well defined and using a coherence measure (as available in the software of the measurement software of the Ono Sokki CF-7200 FFT Analyzer), the degree of reproducibility can be assessed. In measurements in Markneukirchen, the coherence was close to one for almost the entire spectrum, hence the reproducability high. As described before, the observed standard deviation in Fig. 2 is likely an effect of the slightly different sender

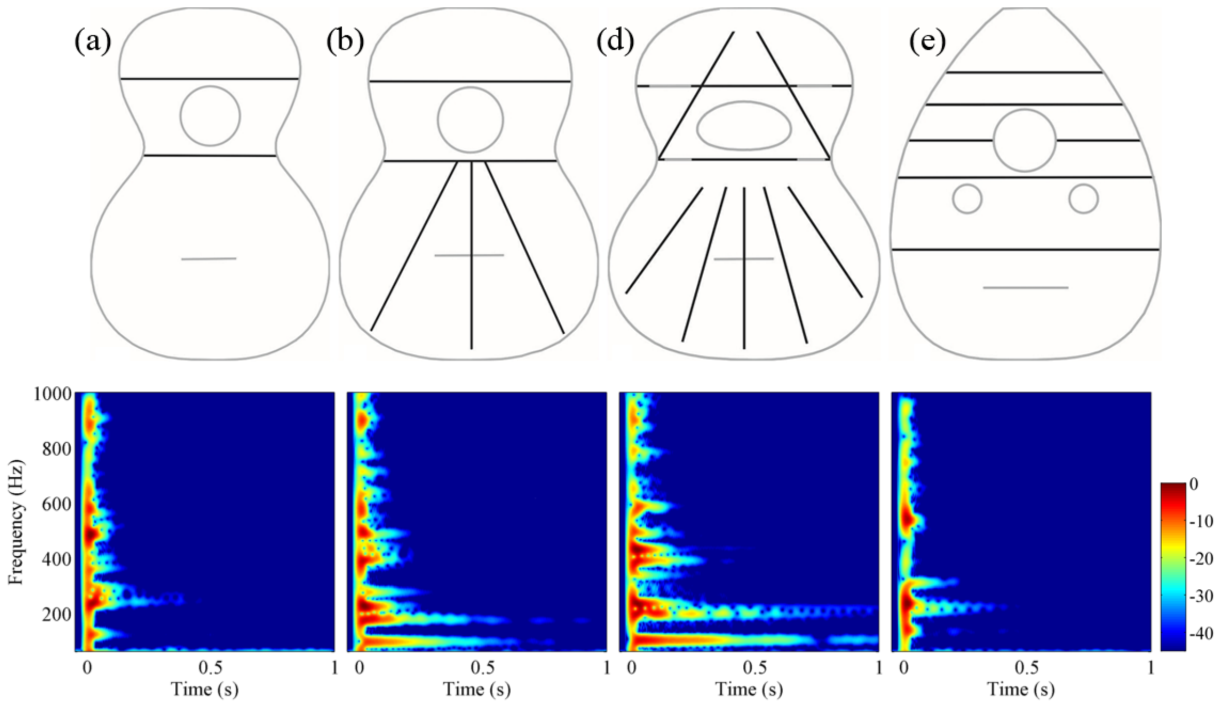

Figure 4. Guitars of the collection of the State Institute for Music Research, with letters corresponding to the rows of Table 1. The upper part of the Figure gives a conceptual drawing of the guitar's composition. The lower part depicts the respective spectro-temporal behavoir.

and receiver locations in the recording of y_r and $y_{\mathrm{r,i}}$. An improved measurement procedure of the AIR method should enable a high degree of reproducibility and a high SNR.

The preconditioning of the signal before analysis needs further sophistication. First the path length between the speaker to the microphone and between the loudspeaker via the instrument to the microphone might be arranged in a way that reduces the temporal overlap between the collateral dirac and the impulse response of the instrument. Furthermore, an improved suppression of the collateral dirac in the signal as well as an improved stabilization in the deconvolution process might enhance the signal quality.

Also the AIR method does not assess mechanical oscillations, as for example the oscillation of the fingerboard, it can deliver an acoustical image of the sounding body. The experience of an auralized AIR-measured impulse responses resembles the effect of finger knocking on the sounding body of an instrument. Given this realistic sound impression, the sonification of historical instruments by convolving recorded strings of different notes with the AIR-measured impulse responses represents an attractive tool for organology as well as for the presentation of historical instruments in museums.

CONCLUSION

In this contribution, a method for measuring the acoustical impulse response (AIR) of the sounding body of stringed instruments has been presented. Because it is a contact-free measurement method, historical instruments, which cannot be evaluated with the hammer probe, become analysable in terms of spectro-temporal behaviour of the sounding body. In a comparison with the hammer probe, the method proved successful in indicating the specific acoustic resonances of the instrument. However, there is no correspondence with the

transfer function retrieved with the hammer probe at large, because the latter incorporates the assessment of mechanical oscillations. With the AIR method, mechanical oscillations are rather captured to the degree of their acoustical radiation. This however, might not represent a drawback. The method measures the acoustical spectro-temporal pattern of the instrument and may supplement the existing measurement techniques for describing, documenting and constructing stringed instruments.
The presented AIR method needs further analysis and sophistication. In future work, a setup for the AIR method must be defined that secures data quality and reproducibility. At the same time, the method should be executable in a standard workshop situation or archive with simple equipment in order to be practical for conservators and instrument builders.

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