Better Understanding the Louvre *Aulos*

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Zusammenfassung

Eine Neuaufnahme des Louvre-Aulos, eines der vollständigsten aus der Antike erhaltenen Instrumente, ergab korrigierte Maße, die hier erstmals vorgestellt werden und mit Hilfe von Computersimulation sowie einem neuen exakten Nachbau zu einer genaueren musikalischen Interpretation führen. Details der Bauweise werden bezüglich Funktionalität und Ästhetik diskutiert.

A pair of wooden pipes in the Egyptian department of the Louvre (inv. nr. E10962) ranges high among direct testimonies of ancient music. It is clearly an *aulos*, almost certainly from the Greek cultural sphere in Egypt, and one of very few complete instruments of this type: only the reed mouthpiece is missing. Wooden *auloi*, especially, hardly ever survive, while the more frequently found specimens made of bone or bone and metal naturally represent but a part, and probably the minor part, of the ancient production. Even though the bone *aulos* established itself as the emblematic form in the Latin name for the instrument, *tibia*, Greek poets often referred to it as *lōtós*, a type of African wood typically used in double pipe production.[1]

The Louvre *aulos* was first published in detail by Annie Bélis, who did not venture to discuss potential scales it may have played.[2] Martin L. West roughly calculated the intervals between individual finger holes on the basis of Bélis' measurements and following the quite reasonable assumptions that (a) a perfect fourth was obtained at a particular position on one of the pipes and (b) the reeds used for the two pipes ought not to differ much.[3] In a former volume of this series ten years ago I published exact calculations, still based on the same measurements (which I only corrected in one case from the photographs provided by Bélis), but undertaken with software I had developed precisely for the purpose of establishing optimal effective lengths for incomplete instruments, which in this case meant finding optimal reeds.[4] The available notes turned out to reflect the Greek model scale of the 'Greater Perfect System', running from its bottom note up an octave and a fourth, just stopping short of the 'overshoot tetrachord' (*tetrákhordon huperbolaîon*). The overall range suggested the possibility of overblowing, which would at least provide the next note in the scale, an octave and a fifth above the bass note. Later I argued that these fundamental design features were probably typical already as early as the fourth century BCE, when they were intimately related to the development of the mentioned model scale, which in turn inspired a particular mathematical scheme of the planetary harmony.[5] Later the examination of another pair in the Egyptian Museum at Berlin, also published in this series, supported the theory of a quite typical design, also substantially reinforcing the hypothesis of overblowing.[6] Surprisingly, even some of the instruments found at Pompeii, though of considerably greater technical sophistication, still maintain the same basic pattern. In view of the identity of all these instruments' lowest notes with that of the 'Perfect System' of ancient theory, I dubbed the emerging class of instruments the *proslambanómenos aulos*.[7] Shortly after my first article in 2004, I also built a replica which confirmed the calculated pitches quite nicely. Nevertheless, I was not happy with the instrument. Irregularities in the pitches, which in theory I had tried to explain in terms of differences of tetrachord shade, a well-known notion of ancient theory, never worked out musically for me. Especially the thumbhole on the lower pipe appeared unusable, and it was almost impossible to get the lowest notes in tune with the rest.

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1 E.g., Euripides, *Helen* 171; *Anthologia Palatina* 16.8.7; cf. explicitly Pliny, *Naturalis Historia* 16.172.

2 Bélis 1984. Before, it had been briefly described in Ziegler 1979, 96 with fig. 115.

3 West 1992, 100–101.

4 Hagel 2004.

5 Hagel 2005.

6 Hagel 2010. For the overblowing mechanism, cf. also Hagel 2012a.

7 Hagel 2009, 332–343.

Years later I compared the available photographs of both sides of the pipes with the help of a computer and discovered that the published position of the problematic thumbhole was apparently incorrect by almost a centimetre. The newly adjusted note at last worked perfectly both on the computer simulation and my replica (which, alas, now revoltingly sported a clogged old thumb hole). All the more I desired to ascertain the rest of the measurements, obtain some additional values that were not available, and build a new, perfect, reproduction. Luckily, Sylvain Perrot obtained permission from the Louvre to study the original together with me and arranged a joint visit. Kindly assisted by Anne Lapasset, we independently obtained measurements of the two pipes, which I later checked using the set of photographs I had taken (including three-dimensional ones) according to the method I described in the preceding volume.[8] The new data, which are presented and analysed in the following, allow for substantial progress in our understanding of the instrument.

The pair of pipes (Fig. 1) bears the inventory number E10962, designated as (a) and (b) by Bélis. However, as her publication seems to apply these labels inconsistently, I will instead adopt an unequivocal 'H' and 'L' for the higher and lower pipe, respectively (Fig. 2). To be sure, since both pipes are of similar length none of them is higher as regards the bass note; but the fact that the finger holes of one pipe both start and end at a higher position than those on the other clearly warrants such a distinction. For all practical purposes, the pipes are of identical length and shape, with matching bulbs and insert sections as well as ornamental incised lines. The bore of Pipe L, measured through the openings with a vernier micrometer, appears to be somewhat wider (7.7 mm) than that of Pipe H (7.5 mm); however, it is difficult to tell whether the small difference is original or, if so, intentional. Both bores flare slightly within the last centimetre or so towards the end, to about 8.5 mm (L) and 8.8 mm (H) (cf. Fig. 3), where there is a small rim on the surface (cf. Fig. 4). Pipe H has nine finger holes, Pipe L only seven: the position of the highest on the latter roughly coincides with the highest but three on the former. As usual on *auloi*, there is only one thumb hole per pipe, located second from the top. The finger hole positions and diameters are listed in table 1 and displayed in figure 2, where their relative orientation is also shown. There are no *sýrinx* holes to facilitate overblowing, such as we find on the Berlin *aulos*.

Within the conical section found immediately below the upper end, the bore widens (cf. Fig. 5): first, in a sharp step of about 1.5 mm, to a little more than 10 mm, and then in a slight cone to 11.4 mm at the exits. This is the insert for the reed, which ensures that its internal wall connects smoothly to the wall of the tube (a reduction of the internal diameter would compromise the tuning of the highest finger holes) and that a relatively large reed can be used, whose blades fan out to a breadth of about 1.5 cm.[9] The inserts reach down to 13.8 mm (H) and 14.6 mm (L) from the upper end, which is about as far down the cone as one could possibly drill without breaking the item, as can be gleaned from figure 2: the wall at the end of the insert is already dangerously thin. Apparently the makers wanted to produce as slim an instrument as possible. In spite of the thin wall, most of the external surface of the cone is additionally recessed by a bit less than half a millimetre; the recess starts from a step slightly above the slimmest point after the bulge (at 17.4 mm from the end) and terminates at a narrow rim at the mouth end (cf. Fig. 6). This recess doubtless contained a sort of reinforcement that prevented the thin wood from splitting when the reed was inserted or adjusting to different degrees of humidity. The most straightforward (and very effective) means is a tight winding of thread. Remains of thread have actually survived in this position on another pipe, from Abusir al-Malaq, that belonged to the Egyptian Museum at Berlin but was lost during World War II (inv. nr. 16401; cf. Fig. 7).[10] The recess at the same time ensured that the winding stayed in place and that the profile of the instrument was perfectly smooth (cf. my reconstruction, Fig. 8).

The decorative lines, four between bulb and main tube, one near the lower end, are probably meant to provide visual balance. The innermost of the four sits at almost exactly a seventh of the entire length, with deviations of 0.3 mm (H) and 0.8 mm (L); this may or may not be intentional. However, it is the distance of the *outermost* line from the upper end that matches that of the single line from the lower end, again with very small errors of 0.5 mm (L) and 0.9 mm (H). In any case, the idea of keeping these distances in balance provides the required motive for the otherwise puzzling fact that the lower line runs across a finger hole on Pipe L.

Both pipes are markedly darker in the region of the finger holes, the discolouration starting at well-defined boundaries 1 cm (L) and 0.5 cm (H) above the respective highest hole. The boundaries are so

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8 Hagel 2012b.

9 Ancient double reeds are manufactured by flattening one side of a length of cane tube; hence if the outer diameter of the cane (= the internal diameter of the insert, or slightly less if a winding of thread was applied) is d_c the blade width is approximately $b = d_c \pi / 2$.

10 The purpose of the winding is recognised in the inventory: "Das Mundstück durch Bewicklung mit Leinenfaden vorm Auseinandersplittern gesichert".

clear that the effect cannot possibly be ascribed to use-wear. Almost certainly it is due to applying some protective substance, presumably a kind of oil. Apparently this substance was precious enough not to be applied also to the uppermost part of the tube, outside the fingered area; on the other hand, the sparing application makes it also likely that the treatment did not originally produce a noticeable difference in colour.

All the finger holes are worked around their edges, both outside and inside: outside, to help sealing them with the fingers more comfortably; inside, probably out of an idea of providing for a smooth flow of air (as opposed to individual fine tuning, which usually seems to have been achieved by adjusting the sizes of the holes instead). Most conspicuous are the recesses for the thumbs (cf. Fig. 9). On a single-handed pipe the thumb is of course crucial in holding the instrument. Unlike the other fingers, one cannot simply withdraw it from the surface in order to open the hole; instead, it must be rolled upwards on its tip. If a glide (in slow melodies) or a seriously misadjusted note (in fast playing) is to be avoided, this rolling must be done very quickly. The observed deep recesses help here: since the tip of the thumb comes to stand outside the recessed area, the same amount of rolling releases a much larger volume of air above the hole than it does on a smooth surface, and in this way the full pitch-raising potential of the opening is realised significantly faster.

Surprisingly, in both pipes both the thumb holes and the lowest holes are displaced to the left in relation to the index finger hole. This is the only fact that might raise doubts against their forming a single instrument, since we would naturally expect opposite arrangements if each pipe was confined to a particular hand. However, this single observation can hardly outweigh the arguments for a double pipe:[11] firstly, they were apparently found together; secondly, they form a perfect musical pair, both in terms of playable intervals and because they complement each other in terms of available notes; thirdly, the meticulous correspondence in their shapes would make no sense if they were never played together, especially in view of the fact that the lower incised line on Pipe L runs right through a finger hole; finally, the structural similarity to the Berlin *aulos* alone might prove the case. On the other hand, the leftwards displacement of the lower holes – which increases towards the exit – is clearly intentional. The only possible interpretation I can see is that the lower part of both pipes is meant to be fingered with the left hand. Though puzzling at first glance, this is not incompatible with the idea of a double pipe instrument, once we let go of the preconception that the association of pipes and hands was rigid.

Two explanations suggest themselves. Firstly, whenever a player availed himself or herself[12] of the lower finger holes of one pipe by closing up the higher ones by means of some kind of plug, it may have been customary to take this pipe (now effectively the lower pipe) in the left hand. This would corroborate a typical association of Left and Low, as was proposed by Stylianos Psaroudakēs on the basis of much older instruments,[13] and it would explain why the thumbhole displacement on the Louvre *aulos* is so small: if the upper range of each of the pipes might have been played with the right hand, it made no sense to make one of them distinctly left-handed. On the other hand, since both pipes have certainly been played also with both hands in top positions (the only way to avail oneself of both thumb holes and therefore all fingers), there was also no point in making both of them markedly right-handed. What we observe is suggestive of the entailing compromise: both thumb holes are just so slightly displaced to the left (and therefore right-handed)[14] that it is not inconvenient to play them with the other hand as well. Possibly the position exactly opposite the adjacent holes and thus right at the bottom was avoided in order to prevent, as far as possible, the inevitably aggregating condense water from exiting through the thumb hole; it is actually quite annoying to play with an increasingly slippery thumb. To be

11 Discussion about their status as a pair had been encumbered by the prejudice that, if it was a pair, it would need a mechanism. So West (1992, 100) rightly acknowledged a single instrument, mistakenly inferring the loss of closure collars (a position that I still considered possible in 2004), while Landels (1999, 279 ns. 19 and 30) rightly rejected the idea of a lost mechanism of this kind, which led him to posit two separate instruments.

12 Actually the distances between the lower finger holes seem to call for male hands. Some women even find it difficult to handle the highest playing position.

13 Psaroudakēs 2008, 201–202; Psaroudakēs 2012, 524 with n. 24. Cf., however, the next note. Also, I doubt that the inclined 'marks' cut into the *Akanthos aulos* can be made to bolster Psaroudakēs' '4L rule': he takes them to run parallel to the thumbs, so as to indicate to which hand a pipe belongs. Certainly an ancient aulete did not need to search for funny marks to establish how to handle a pair of pipes – at least not if there was a clear-cut association between the longer pipe and the left hand, as Psaroudakēs argues. Rather, I think that the marks were functional, helping the thumb tips to maintain a grip on the tube when the thumbs were rolled upwards to release the hole. This, however, assigns the pipes in the opposite way, since the thumbs must then run towards, not alongside the marks.

14 This runs contrary to Psaroudakēs' conclusions,who suggests that thumb holes were displaced in the direction of the playing hand; however, the idea of two left-handed thumb holes is irreconcilable with the fact that the lower holes on both pipes are also for the left hand (and clearly so). Such a layout would make both pipes left-hand pipes of different pairs, which is hardly an acceptable conclusion.

sure, breaking up a strict correspondence between pipes and hands is by no means a desperate move. Some of the transmitted performance instructions for Roman comedies clearly imply that, although certain pipe designs were typically assigned to the right and the left hand respectively, actual practice quite regularly disregarded this correlation.[15]

Secondly, it is conceivable that the two pipes did *not only* perform as a pair but were *also* used as single melodic instruments played with both hands – in which case the left hand would always take the lower position. This reminds one of the quick change between a paired *tibia* and a single-pipe *mónaulos* that served as the model for a distich by the Roman first-century CE poet Martial.[16] With real instruments such a process might be envisaged as being much more seamless if the player was concerned with just one pair of reeds. Both explanations, switching between hands and alternative employment as single pipes, are of course not mutually exclusive; it is more likely that ancient players exploited their instruments' full potential.

With the corrected data fed into my software, the optimal effective reed lengths now turn out to be practically identical, measuring 4.03 cm (H) and 4.15 cm (L).[17] The resulting theoretical pitches are given in table 2 and the major consonances between them in table 3; the screenshot in figure 10 provides a graphical display, detailing also ancient note signs associated with the individual pitches. My new replica, with properly adjusted reeds, confirms the results, playing in effortless unison with the calculated pitches as emitted from the computer.[18] The instrument's overall scale is now very familiar: with a single exception, no pitch deviates from either a Pythagorean or an equally tempered diatonic by more than a fourteenth of a tone. The exception is the highest hole but two on Pipe H, which is off by almost a fifth of a tone. However, in this highest region of the instrument the holes generally need to be quite closely packed, and especially so where there is only a semitone between them. This is precisely the case for the hole in question, which stands below a semitone step. Hence its slight displacement towards the lower end is plausibly a compromise between an exact diatonic scale and convenient fingering, which here calls for more balanced spacing than a clear tone-semitone dichotomy would warrant. A comparable phenomenon has been observed on the Berlin *aulos*.[19]

However, if some kind of intentional compromise on the part of the makers was involved here, we may still wonder why the shift was not divided between the two semitone-bounding holes, shifting the upper one – which is the thumb hole – upwards as well. Perhaps this question is sufficiently answered by pointing to the fact that the higher holes are slightly closer together anyway, so it made more sense to reduce the wider space. However, it may be worthwhile to recall a suggestion I have made concerning music of the Roman Imperial era: a statistical analysis of the surviving melodies indicates that the musical function of the note *parámésē* (best transcribed as *b*) was no longer that of providing a fifth above *hypátē* (*e*); instead it more regularly belonged to the harmonic domain of *diátonos* (*g*), with which it forms a major third.[20] Now the Louvre *aulos* does not play the respective scale at the same pitch as the standard cithara. Functionally, however, the shifted hole is its *parámésē*, and therefore it is conceivable that the down-tuning of this hole reflects a process similar to what was done, for instance, on the cithara, aiming at a pure third with '*g*' more than at a pure fifth with '*e*'.

Be that as it may, the number of attainable consonances (within a consistently defined error margin) proves to be a good measure of data quality. In figure 11, the respective results are given first for my original calculations based on Bélis' figures with one small correction, then for those with the additional correction of the thumb hole of Pipe L, and finally for the new measurements presented here.[21] The progressive increase in consonances, which would hardly arise from random shifts in the data, also demonstrates the validity of the approach of using these very consonances to determine an optimal reed configuration.

In my initial publication, I pondered the question of the 'key' (*tónos*) in which the Louvre *aulos* may have played and identified it as, most probably, Hypolydian.[22] In view of the Berlin *aulos*, which is structurally similar but higher in pitch, I later concluded that these were 'transposing' instruments, which came in different sizes and may not have taken part in the system of notational 'keys' at all. Rather, it would appear plausible that music for them was notated (if at all) in the 'natural'

15 Cf. the Didascaliae to Terentius' *Eunuchus* and *Heautontimorumenos*: *tibiis duabus dextris* "with two right-hand pipes".

16 Martial, *Epigrammata* 14.63(64): *Ebria nos madidis rumpit tibicina buccis*: / *Saepe duas pariter, saepe monaulon habet*. "Frequently she holds two (pipes) at once, frequently a *monaulos*."

17 Cf. the difference between the 4.2 cm (H) and 4.6 cm (L) obtained in Hagel 2004.

18 For the replica I have used wood from *Celtis australis*, which ancient references to *lōtós* trees are generally taken to mean, most generously supplied by Paul Reichlin. However, the original wood seems to be darker (though this is difficult to ascertain given its age and the fact that it was treated with a substance that has obviously darkened over time) and probably harder.

19 Hagel 2010, 71.

20 Hagel 2009, 230–239.

21 Cf. the analogous diagram for two of the Pompeii pipes in Hagel 2012c, 110 fig. 1.

22 Hagel 2004, 384.

Lydian *tónos* (structurally corresponding to a scale without any sharps or flats); there are some scores that seem to be relevant here.[23] At any rate, if the Louvre *aulos* ever played together with a standard-size lyre, the strings of the latter would have been tuned to Hypolydian in order to match the notes of the former.

With different sets of finger holes open or closed with plugs, it becomes possible to play in quite a variety of 'modes'. I gave examples for several – though by no means all – of them in my analysis of the Berlin *aulos*; especially applicable are those associated with figures 6, 7, 8 and possibly 9 there.[24] Over the last years, I have increasingly felt that among all the possibilities, those realising a *G* mode are most fitting for *auloi* of this type, most of all because of the structural '*d*' as the highest note; but I am certainly far from having fully explored the whole diversity of available options. A couple of sound examples produced on my new replica can be found on the CD that comes with this volume (Track 1 and 2).

A final word is in place about the possible date of the artifact, as I cannot see any argument for the original dating to the fourth century BCE.[25] We do not have any find context – not even the rough provenience is known – or a radiocarbon dating. It is true that we may well expect a similar general design already as early as in the fourth century BCE; but it is certainly much likelier that this particular instrument dates from a much later period, anything between late Hellenistic to Roman Imperial. At any rate, it seems to fit well with what else is known about music in the Roman Empire.

Acknowledgements

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23 Hagel 2009, 332–343.

24 Hagel 2010, 79–81, with tracks 1–5 on the accompanying CD.

25 So Bélis 1984, 122; quoted with a question mark in West 1992, 98.

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Tracklist

Track 1 1:13 min.
Louvre *aulos* – Ionics.

Track 2 2:46 min.
Louvre *aulos* – Improvisation.

Pipe L		
length: 403.0 mm external diameter: 13.6–13.7 mm bore diameter: c. 7.7 mm, widening to 8.8 at exit		
finger holes		
nr.	size (mm) $Ø_l \times Ø_t$	distance from lower end of pipe (mm)
1	6.0 × 5.8	56.1
2	5.9 × 5.8	76.5
3	6.4 × 6.0	116.3
4	6.4 × 6.0	146.4
5	6.4 × 6.0	164.4
6	6.4 × 6.0	199.7
7	6.4 × 6.0	223.1

Pipe H		
length: 402.6 mm external diameter: 13.3–13.8 mm bore diameter: c. 7.5 mm, widening to 8.5 at exit		
finger holes		
nr.	size (mm) $Ø_l \times Ø_t$	distance from lower end of pipe (mm)
1	6.3 × 5.8	73.0
2	6.3 × 5.9	119.2
3	6.3 × 6.0	150.3
4	6.1 × 6.0	165.9
5	6.5 × 6.0	198.6
6	6.2 × 5.9	223.4
7	6.8 × 5.5	243.9
8	6.6 × 5.5	257.9
9	7.8 × 6.6	278.5

Tab. 1 Measurements of acoustical importance.

	Exit	Finger Holes									
L	0	1	2	3	4	5	6	7			
	183.5	206.4	218.5	243.9	269.5	288.3	327.8	363.5			
H	0		1	2	3	4	5	6	7	8	9
	182.6		214.6	244.2	271.2	288.3	324.7	362.0	400.9	433.3	490.0
	A+4	*B*+17	*C*+15	*D*+5	*e*–11	*f*–5	*g*+1	*a*–3	*b*–34	*c*+1	*d*+14

Tab. 2 The calculated optimal scale with indications of relative pitch.

Deviations in cents from an equally tempered diatonic scale (Aristoxenus' *diátonon sýntonon*) based on relative '*a*' = 363.8 Hertz.

Between Pipes L and H			
interval	hole on 2	hole on 3	dev.
1 : 1	0	0	+9
1 : 1	2	3	+2
1 : 1	3	4	+11
1 : 1	4	5	+0
1 : 1	5	6	+17
1 : 1	6	7	+7
2 : 1	0	7	–8
2 : 1	8	2	–14
2 : 1	9	3	+8
3 : 2	5	2	–16
3 : 2	6	3	–18
3 : 2	2	7	–13
3 : 2	7	4	–15
3 : 2	8	5	+4
3 : 2	9	6	–6
4 : 3	0	3	+3
4 : 3	2	0	–3
4 : 3	1	5	+13
4 : 3	4	2	–18
4 : 3	5	3	–3
4 : 3	2	6	+12
4 : 3	6	4	+13
4 : 3	3	7	+9
4 : 3	8	6	–15
4 : 3	9	7	+19

Within Pipe L			
interval	hole 1	hole 2	dev.
2 : 1	0	7	–16
3 : 2	2	6	+1
3 : 2	3	7	–11
4 : 3	0	3	–5
4 : 3	2	5	–18
4 : 3	3	6	+14
4 : 3	4	7	+20

Within Pipe H			
interval	hole 1	hole 2	dev.
2 : 1	0	6	–15
2 : 1	1	8	+17
2 : 1	2	9	+6
3 : 2	0	3	–17
3 : 2	1	5	+15
3 : 2	2	6	–20
3 : 2	4	8	+4
3 : 2	5	9	+11
4 : 3	0	2	+5
4 : 3	1	4	+13
4 : 3	2	5	–5
4 : 3	3	6	+2
4 : 3	5	8	+2

Tab. 3 Calculated consonant intervals. Finger holes are counted from the lower end of the instrument, with '0' representing the tube with all holes closed.

Intervals are labelled by ratios of frequencies: 1 : 1 = unison; 2 : 1 = octave; 3 : 2 = fifth; 4 : 3 = fourth; 'dev.': calculated deviation from pure interval (up to ±20 cents).

Fig. 1 The Louvre *aulos* (E10962) (photograph by Stefan Hagel; courtesy Louvre Museum).

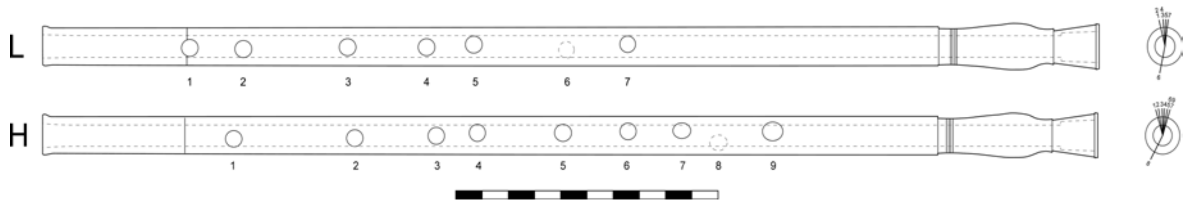

Fig. 2 Overall structure, position and orientation (right) of finger holes (drawing to scale by Stefan Hagel).

Fig. 3 Exits (photograph by Stefan Hagel; courtesy Louvre Museum).

Fig. 4 Lower ends (photograph by Stefan Hagel; courtesy Louvre Museum).

Fig. 5 Mouth ends with reed inserts (photograph by Stefan Hagel; courtesy Louvre Museum).

Fig. 6 Bulbs and reed-insert cones (photograph by Stefan Hagel; courtesy Louvre Museum).

Fig. 7 Remains of thread winding on Berlin ÄM16401 (photo courtesy Berlin Egyptian Museum).

Fig. 8 Replica: bulbs and reed-insert cones with a winding of thread (reconstruction and photograph by Stefan Hagel).

Fig. 9 Thumb hole recess on Pipe L (photograph by Stefan Hagel; courtesy Louvre Museum).

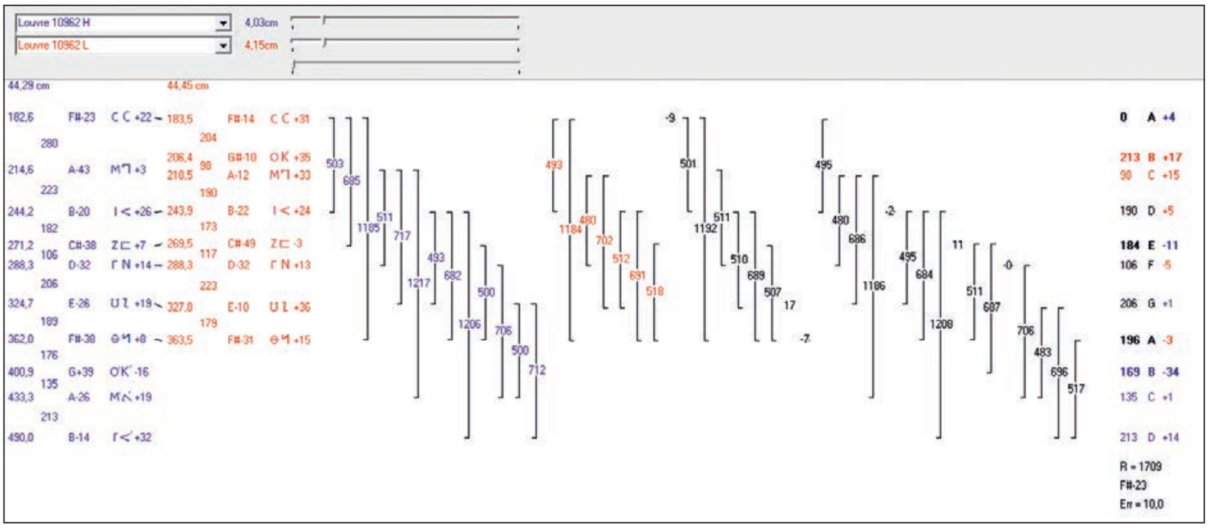

Fig. 10 Calculated optimal pitches and intervals (made by Stefan Hagel).

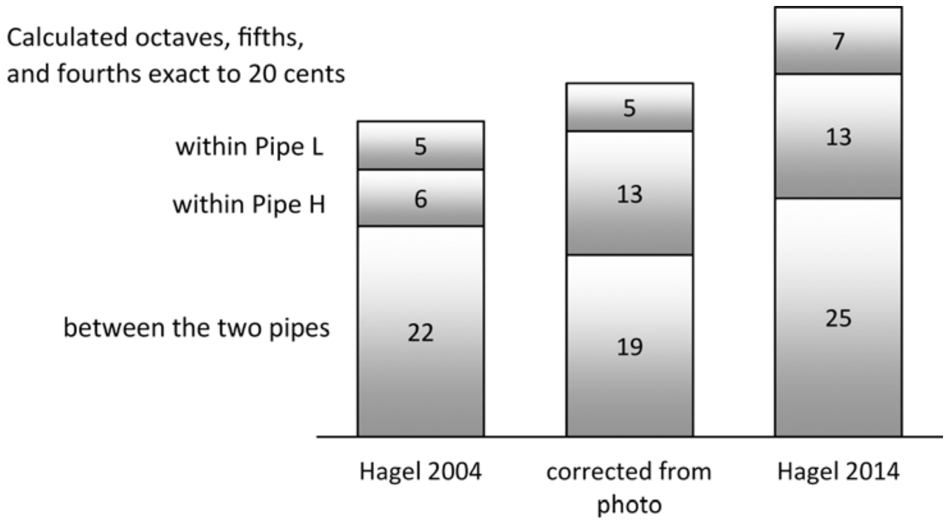

Fig. 11 Number of calculated concords up to ±20 cents increasing with measurement accuracy (made by Stefan Hagel).