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ASSESSING UNKNOWN PARAMETERS OF INSTRUMENT FINDS BY WRITING SOFTWARE

1. Introduction

The computer world has evolved considerably since I began using the computer to explore ancient music. Nevertheless, the reader, should he/she not abandon this contribution right now, will find that the author has been sticking to old-fashioned approaches wherever possible. The following is therefore partly a defence against the expectations inevitably raised by a world of shinier software, which however, I will argue, fosters a tendency towards mustering astounding resources for very limited or indeed questionable goals. Under the pretext of sharing some of my general experiences it will briefly develop into a rant, which I justify beforehand with what is at stake, politically: the waste of considerable public resources, made possible by a deficient reviewing system. I do not claim that ill intention necessarily forms the core of what I feel might (and perhaps should) develop into a major crisis of public trust in our science. As with so much that goes wrong, initial basic misapprehensions may simply propagate themselves up to a point when it is too late to pull the breaks without considerable self-sacrifice.

As researchers we may be accustomed to observe such mechanisms in enthusiasts from outside academia, whose lack of connection with the bibliography and with methodologies that keep us alert to potential fallacies have led them to fantastic conclusions heralded in social as well as conventional media. All the more it may escape us how little we are ourselves protected from similar errors whenever we venture outside our expertise. The ensuing problems expose themselves with exceptional clarity in a field like music archaeology that is still novel and lacks a solid tradition handed down in university courses. Music archaeologists turning to computer people will normally not know what the available algorithms can do – and will habitually overestimate their potential.

Experts for sound-related software engaging with archaeologists, on the other hand, will habitually overestimate the input to expect both in terms of quality and comprehensiveness. This state of mistaken confidence unavoidably makes itself heard in grandiose grant applications, in a scientific environment that has learnt to counter the shockwaves of Thatcherism with the abolition of humility. Reviewers will not normally be equally at home at both sides of the conceptual abyss, consequently share the misapprehension of the other side's potential, and therefore overlook potentially disastrous implications of those limits with which they are familiar. If a project is finally implemented, however, and if project communication works as it should, the truth may sooner or later dawn on its members[1]. In a worst-case scenario, this leads to the publication of what, for all practical aspects, would need to be termed fake results: valid products of computational modelling, while everybody involved is aware, on some level of bad consciousness, that these heavily depend on parameters way beyond any evidence and are perhaps produced by algorithms that do not really apply to the investigated material.

As I said, this is the worst case, and there are many grey shades of more or less compromised results and different portions of researcher souls sold to the promises of career and recognition. But how to avoid the allure? Of course, at least when we find ourselves in the role of a reviewer, keeping aware of the mechanisms outlined above may already help. When planning a project, on the other hand, I am afraid this will not suffice. Here a solid foundation can only be laid when a profound knowledge of the potentials and limits of all involved methodologies, archaeological, iconographical, philological, ethnological, you name it, is assembled within the single brain of at least one person. Nota bene, the potentials and limits, not all the technical details and procedures.

This may of course be achieved during intense exchange in the planning phase, where a potential PI from the music-archaeological side must not recoil from investigating what existing or planned software (which for him/her, as such, may remain a black box) needs to be fed and what it can produce with which degree of reliability as well as, crucially, how uncertainties in various parameters would affect the results. On the other hand, a PI who is primarily software expert would need to press his/her colleagues about the reliability and comprehensiveness of their data, familiarising himself/herself with all the uncertainties in the interpretation of the archaeological record, with iconographical and literary conventions and invention, knowns and unknowns about ancient aesthetics, or also pronunciation and vocal styles. He/she might also be well advised not to rely on a random colleague from a particular field just because this colleague happens to sit next door: comparatively few philologists, for instance, would be all too well informed about the sound of the ancient living voice.

Sadly, not a few projects might die at this stage, for instance when an archaeologist finds he/she needs to abandon the idea of reconstructing the soundscape of a building where we do not know if its walls might not have

[1] While I recommend the described model as an interpretational framework because it reduces the assumption of ill intent to a minimum, I must confess it may fail in some cases. One particularly infamous in music-archaeological circles was the ‘virtual reconstruction’ of a harp (wrongly termed ‘epigoneion’) by a project named ASTRA about a dozen years ago, which seems to have been flawed on many levels from the outset.

been covered in tapestries. There is an undeniable unfairness in this approach – the most honest and committed researchers stand the least chance ever to apply for funding – for which to compensate is once more the responsibility of reviewers.

From these preliminaries it may have become clear why I recommend the closest possible proximity between programmers and music archaeologists. In the following it remains to explain the advantages of the extreme case: personal unity. As everything, these come at a cost: making software work, and more, making it work in an intuitive way that integrates as seamlessly as possible within one's scientific workflow, can consume a lot of time. On the other hand, it can also be a lot of fun. Exploring uncharted territory, facing towering obstacles, iterated frustration with futile attempts, finally the joy of an elegant solution behind which the hideous shadows of subsequent challenges lurk, all this may make your working hours the rewarding experience in the quest for which others need to waste their free time gaming in front of just the same kind of screen.

2. The example of the *aulos*: what to model

In order to describe the more scientific gains, we need to settle on a particular case study. Among my attempts at computational research on ancient instruments, my experience with doublepipes is by far the most extensive. Back in 1997, starting from Martin L. West's interpretations of the *aulos* measurements available to him (West 1992, 97-101), I undertook refining his rough calculations that were based solely on hole distances by employing precise formulas that take into account bore and hole diameters as well as wall thickness, and potentially the effects of cross fingering or 'open' versus 'closed' playing (playing styles in which all holes beneath the one principally sounding the actual note are left open or closed respectively). Even the nature of the formulas evidently requires the use of a computer; the need for some proper software emerged from the fact that one crucial parameter was always unknown, namely the extension of the vibrating air column at the upper end, next to the player's mouth. Sometimes only the reed itself was missing, often including the frail top part of the pipe into which it fitted, and in other cases the entire upper part of a pipe was lost. In any case, this would require numerical experimenting with a large number of possible lengths.

In this endeavour, I have been primarily interested in the reconstruction of instrumental pitches that would hopefully emerge meaningful in terms of ancient music-theoretical writings and in turn elucidate the practical background of these. This is very different from virtually reconstructing the actual sound of an instrument. This would have required very different technology, incomparably more computing time and processor power without promising meaningful results.

In a reed-driven instrument, the quality of the sound depends to a large degree on the properties of the reed, and therefore on a factor which was almost entirely unknown when I started my research. Moreover, the sound of each *aulos* pipe is also influenced significantly by the coupling of the oscillatory regime of reed plus tube to the secondary resonator of the mouth cavity and, via this and the player's lips, to the other pipe, which drastically encumbers physical modelling. Meanwhile, with much experimental work, we have learned to produce reeds that match the ancient iconography; but this has only reduced the potential variability of the unknown parameters.

Even today, it therefore seems to make little sense to compound uncertainties in the input data with inaccuracies in physical modelling when more accurate results can easily be gained by actually sounding a replica or working model. Contrarily, a similar replica-based approach is not viable when it comes to assess the pitches of a reed instrument (though it may work quite well for flutes, see Terzēs 2020). Firstly, since at least one important variable is always unknown, a series of practical experiments would need a large number of different reeds, which is unfeasible.

More importantly, reeds are flexible and lend themselves to bending the intonation that is 'built into' an instrument. This is an advantage whenever the instrument is poorly tuned or for some other reason cannot produce all required notes straightforwardly, for instance when a musically precise positioning of finger holes conflicts with the physiology of the human hand (Hagel 2010, 71). When exploring a sound tool from another culture, however, it turns into an insuperable obstacle, because every modern experimenter who is sufficiently versed in playing reedpipes will unconsciously bend the notes emitted by each fingering in a way to fit his/her musical expectation. The computer, in turn, will render unbiased sets of pitches that rely solely on the physics of the pipe. Whenever we are dealing with an expertly made instrument – which is *a priori* to be assumed for all the expensive pipes with mechanisms, and has *a posteriori* emerged for others as well – the computer can thus be expected to help assessing the musical intentions of the original makers and consequently the musical expectations of performers and audience within the relevant cultural horizon.

3. Developing an integrated research environment

While it might have been feasible to reuse some pre-existing software for predicting woodwind pitches, this would have put tight limits on my research. Almost all modern music software is conceptually tied to the idea of an equally tempered scale, often also to a concert pitch of A440, which entails

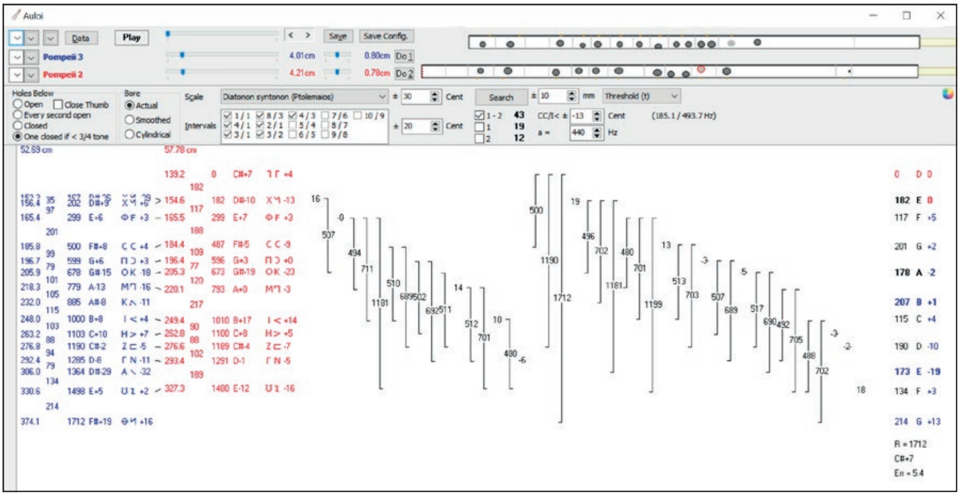

Fig. 1 – Software calculating pitches for a given instrument design with reeds of specific effective lengths. Example from Naples Archaeological Museum inv. 76892 and 76893, two pipes retrieved from Pompeii. Image Stefan Hagel.

not only considerable inconvenience but also a built-in methodological bias that is hard to eliminate. Every single output – bearing in mind the necessity of innumerable calculations while experimenting with missing parameters – would thus require to be transformed, in a secondary step, in order to display its relation with the musical structures of the ancient world, a world of a different, probably more flexible pitch standard, and of a whole flurry of fine tunings recorded by ancient authors, only two of which come reasonably close to a grid of equal semitones. Having my software purpose-made thus meant integrating meaningful output values from the start (Fig. 1).

In addition to opaque frequencies in Hertz and slightly more approachable intervallic steps in cents, as well as the deviations from roughly equivalent modern notes, it was thus possible to print each resulting pitch as its equivalent ancient note as well, of course again including the deviation from an abstract ancient semitone grid[2], using the most recent assessment of the ancient pitch standard, which has long been agreed within a range of less than a tone (West 1992, 273-76; Hagel 2009, 68-95). In addition, it becomes possible to match any calculated set of pitches with interval sequences described by ancient authors, either in terms of fractions of tones in the harmonicist tradition, most prominently represented by Aristoxenus, or in terms

[2] For mapping out ancient pitch space in this way, see Aristides Quintilianus 1.11, 24-27 Winnington-Ingram. Note that these pitches do not as such form practical scales.

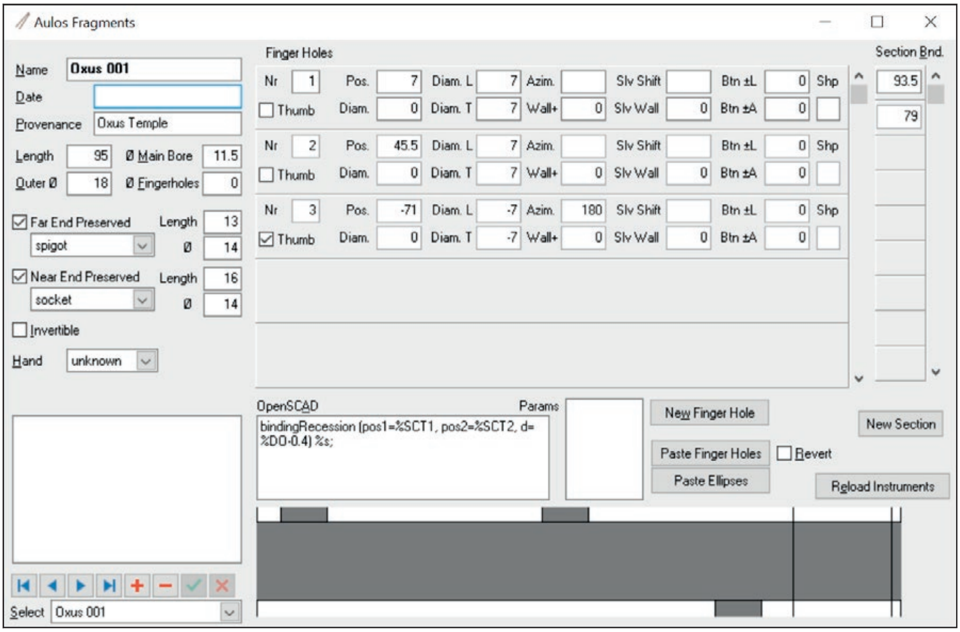

Fig. 2 – A data form describing the physical properties of an *aulos* section. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

of the ratios both transmitted and newly derived by Ptolemy – or also scales suggested in modern scholarship or found in the ethnological record. In this way, what would otherwise involve tedious procedures of data transfer and separate evaluation is achieved in the blink of an eye, all integrated within a tailored graphical interface.

Behind the scenes, of course, the relevant data need to be stored. Originally I designed a Microsoft Access relational database, to which my software connected via ODBC, with separate tables describing fragments, sections and tone holes on fragments, including the position of buttons operating a potential sleeve mechanism, joining capabilities between fragments, possible (or certain) arrangements of fragments to pipes, and finally, where feasible, of pipes to instruments (Fig. 2). Such a local database comes with the considerable advantage of permitting all kinds of work without Internet connection, which was prerequisite in the 90ies but can still be useful when working in Museum basements or while travelling. With this combination of relational database and graphical user interface it has since been possible to obtain consistent musical interpretations of numerous *aulos* finds, whose predicted pitches were always closely matched by the replicas (Hagel 2004, 2008, 2010, 2012, 2014, 2020).

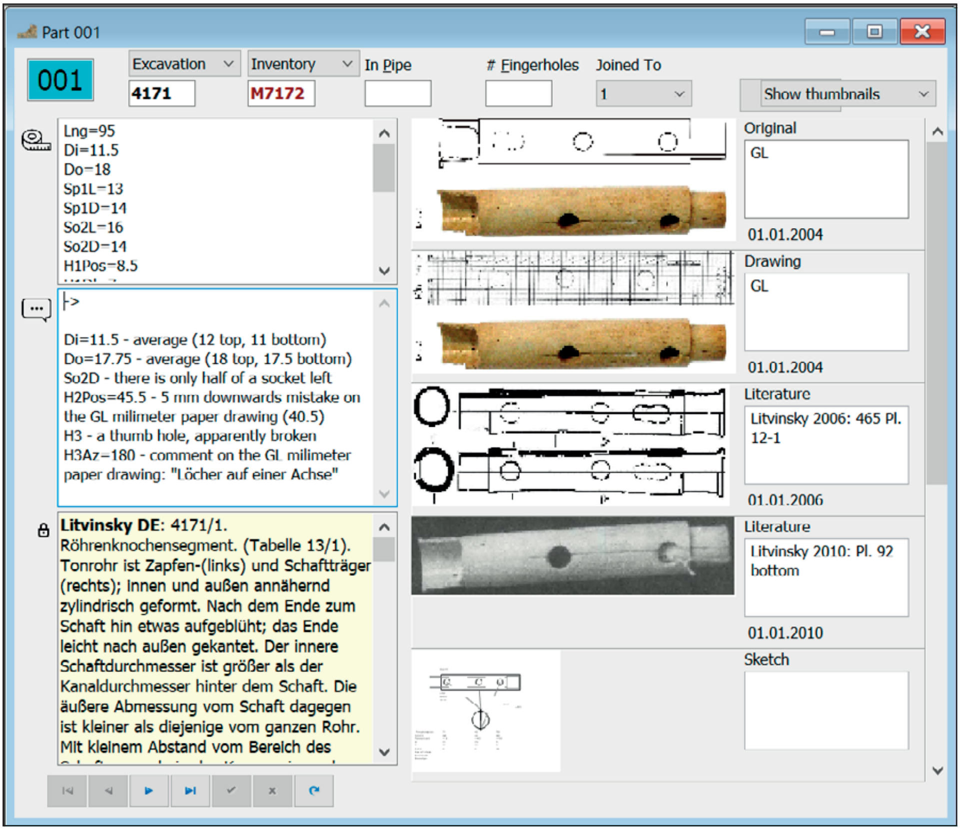

Fig. 3 – A data form collecting the evidence for an *aulos* section. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska, Boris A. Litvinsky. Image Stefan Hagel.

In a more modern world, and with increasing interest in the field and the establishment of collaborative projects, I have devised a complementary online database, coming with a desktop front end that connects to a mySQL server (Fig. 3). Here we store and link to image data such as photographs and drawings as well as modern literature, include competing identification systems such as find and inventory numbers, but also information about the viability of physical joints and the placement of individual fragments within tentatively assembled instruments. Together with Olga Sutkowska we have also devised a comprehensive system of sigla for all kinds of relevant measurements, enabling collaborators to include whatever technical information is available. The data can then be transferred directly to the evaluation software, whenever required.

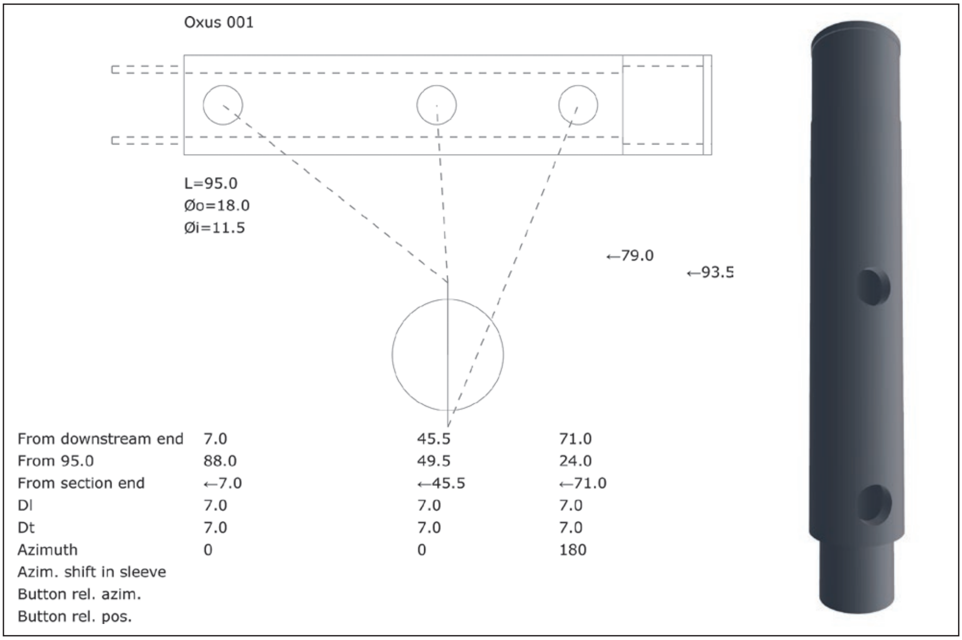

Fig. 4 – SVG sketch of an *aulos* section and printable *aulos* part. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

From the same data, it is furthermore possible to create schematic SVG sketches as well as printable 3D models in OpenSCAD descriptive language (for concision using functions from an *aulos*-specific module I have written) (Fig. 4). With proper printing technology, such as selective laser sintering (SLS), the latter may yield fully working models, even up to imitating the rotating-sleeve mechanism of Roman-period instruments.

These interfaces are crucial for the quality management in our projects (Fig. 5). Firstly, errors inevitably creep in during the process of taking measurements – often hundreds on a single day – and transferring these to the computer. With an automatically generated transparent sketch, with which photographs of the objects can easily be overlaid, errors down to a millimetre or even less are readily discerned and can consequently be corrected. The fully integrated approach, on the other hand, ensures that no further transmission errors are to be expected in the course of most of the workflow. The working models, for instance, will follow the specifications up to the precision of the used printing technique. In this way, they are reliable tools for testing the acoustic predictions of the software in practice, and may even serve as performers' instruments.

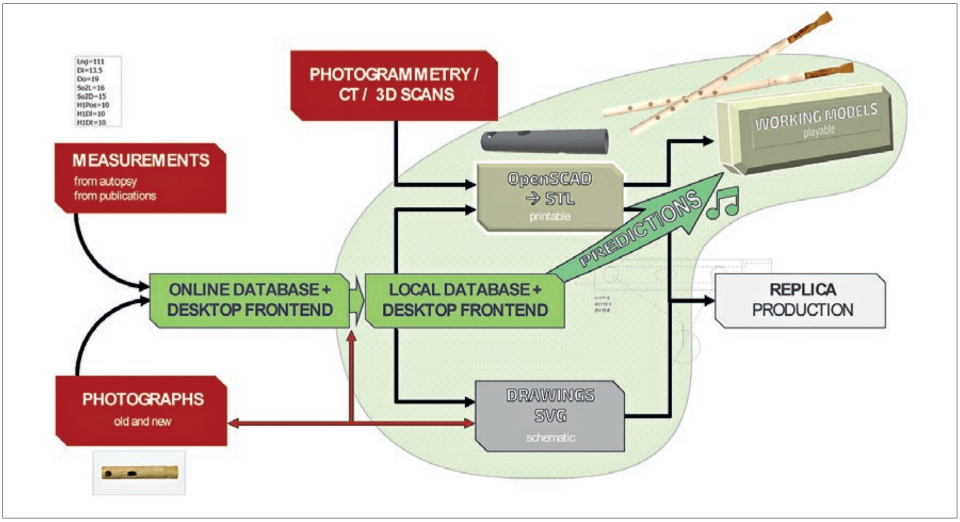

Fig. 5 – Workflow from artefact to interpretation and replication. Within the green area, copying errors should be excluded. Image Stefan Hagel.

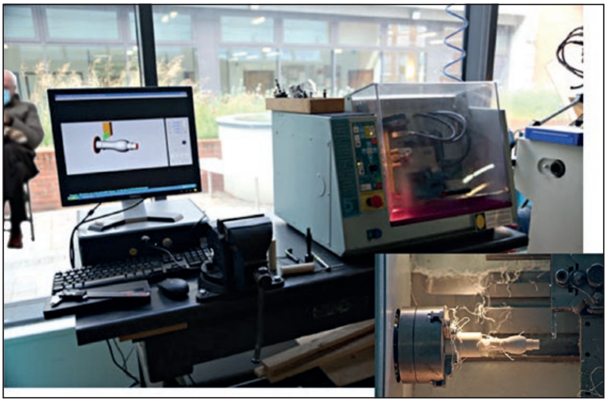

Fig. 6 – Manufacturing part of an *aulos* bulb+insert assemblage on the CNC lathe at Middlesex University, London. Image Neil Melton, Peter Holmes.

Equally importantly, sketches and printed models are of invaluable help in the process of manufacturing actual replicas by traditional means. Not only are copying errors once more excluded; even more importantly, many communicational hurdles regarding the conceptualisation of relative positions and, above all, azimuths are easily avoided by providing a three-dimensional

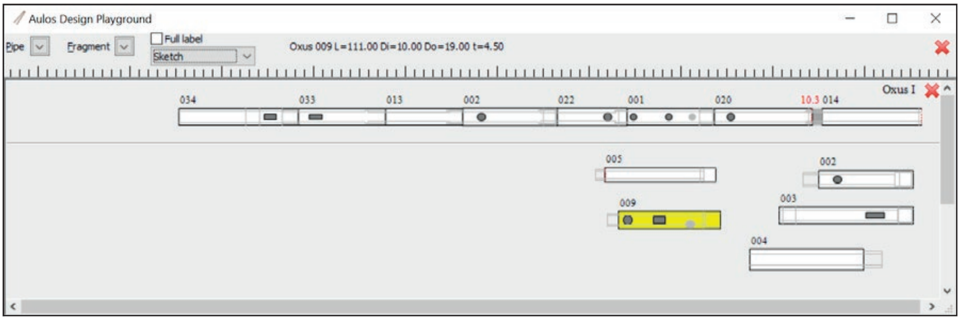

Fig. 7 – Module for experimental assemblage of *aulos* parts. Random example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

model of the final product. If parts of the production process involve computer numerical control (CNC), the respective input may also be derived from available formats (Fig. 6).

For the scholar, a useful by-product is the export of any data regarding either physical dimensions or the relation of predicted pitches in numerical and graphical formats, facilitating the production of diagrams and illustrations for publication. Since their dimensions thus reflect the numerical data precisely, they can easily be juxtaposed with data from other sources.

More recently, when we started to work on the highly fragmented instrument finds from Queen Amanishakheto's pyramid tomb at Meroë (Bodley 1946; Gänsicke, Hagel 2017; Hagel 2019), on the one hand, and from the Oxus temple in present-day Tajikistan (Litvinsky 1999, 2010, 424-53), on the other, it became evident that the search for physically possible as well as musically meaningful configurations of fragments required manipulating such configurations on the computer quickly and efficiently, while maintaining a live view on the ensuing pitch predictions. At this stage, a reliance on pre-existing software would once more have been detrimental. Instead, it was not all to difficult to augment our software with a new module, where the fragments can be assembled graphically using the mouse, dropping them into experimental instrument designs, or flipping them around by double-clicking (Fig. 7).

4. Robust optimisation of unknown reed lengths

As much as an extensive use of the possibilities that modern computing offers may advance music-archaeological research, its value can never be greater than that of the methodologies which are written into the software. However, as has been argued in the outset, the combination of the very different worlds of an ultimately humanities-rooted subject, on the one hand, and computer sciences, on the other, both coming with mutually intimidating languages, lends itself much more readily to the temptation of obfuscating than is possible when staying within a single well-ploughed field of expertise. It will be useful to analyse a specific *aulos*-related example, which bears on the question of what computer-assisted 'optimisation' may meaningfully represent.

In the foregoing I have described the universal problem of establishing the 'correct' effective reed length, often including a missing upper pipe end. If the intended scale of an instrument were known beforehand, this problem might be rephrased to finding the total length which produces the smallest deviation from that scale. However one might define 'smallest deviation' for that purpose, with an ancient instrument we will hardly ever find us in the lucky position of knowing the makers' musical objectives in advance. For that reason, a more general approach is needed. Since ancient harmonic analysis had been centred on pitch structures bounded by pure fourths, fifths and octaves, intervals that are found to be of primary importance also in ancient Near Eastern musical sources, it appears reasonable to maximise the number of such intervals, in addition to unisons.

Of course, no material interval is ever 'pure' in the mathematical sense of the word, with its implication of infinite precision. The optimal configuration might therefore be defined as containing the greatest number of near-pure intervals, with a smallest total deviation. However, finding a meaningful formulaic expression for that idea is less straightforward: how would the number of intervals and the respective deviations be weighted against each other? I have found it practical to first introduce a threshold value for the inclusion of intervals, then establishing the largest possible number of these, and only in a final step use the deviations to find the precise optimal configuration for the pre-established maximal number of intervals. This has the advantage of yielding intuitive results, which can also be displayed graphically in the form of the 'admitted' intervals (Fig. 1). A more refined algorithm would weight each applicable interval (most practically, for instance, each interval that lies within a quartertone of the ideal) according to its deviation from the ideal, counting it fully only when it is precise. Modelling human perception requires that intervals that are only a few cents off are still assigned relatively high values, which then need to drop rather quickly to near-zero for greater deviations. The corresponding bell shaped curve is conveniently modelled as a Gaussian function of the deviation d (expressed in logarithmic units such as cents) with a maximum of 1 and a standard deviation σ (expressed in the same units) that reflects the tolerance level:

$$f(d) = e^{-\frac{d^2}{2\sigma^2}}$$

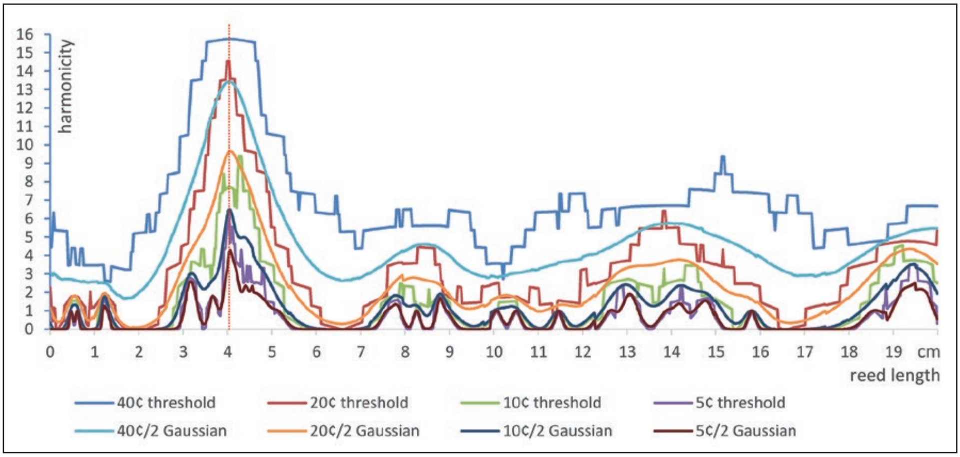

Fig. 8 – Robustness of reed length optimisation: Louvre E10962, high pipe. Red dotted line: predicted optimal reed length.

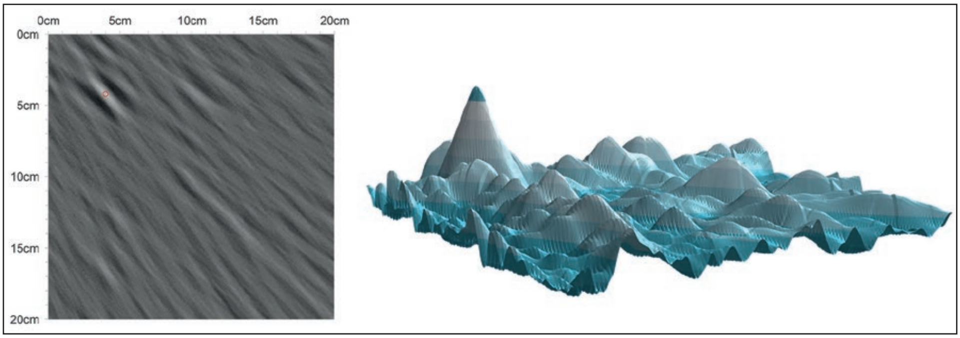

Fig. 9 – 'Harmonicity map' for various effective reed lengths configurations as colour map (threshold, 20¢) and surface plot (Gaussian, σ=20¢/2). Lighter areas (left) and higher elevations (right) indicate a larger number and higher quality of near-pure unisons, octaves, fifths and fourths. The optimum occurs at (4.01 cm; 4.21 cm); cfr. Fig. 1. Example from Naples Archaeological Museum inv. 76892 and 76893, two pipes retrieved from Pompeii. Image Stefan Hagel.

Fig. 8 shows the robustness of both approaches over a wide range of tolerance levels, using the example of intervals within a single pipe. The ragged lines reflect the threshold approach; the smooth contours, Gaussian weighting. The thresholds are varied over a factor of eight, ranging from 5 to 40 cents for the simple algorithm, and the respective half values for the standard deviation in the weighted approach (in this way, the inflection points of the bell curves coincide with the respective thresholds). Nevertheless, in spite of the fundamental differences in the algorithms as well as the extreme variation in the tolerance parameters, the predicted optimal reed length remains identical within less than a millimetre.

For a most intuitively useful threshold value, I have in practice settled on 20 cents, the tenth part of a tone, which easily accounts for small measuring errors as well. It falls just short of the so-called syntonic comma, an interval that Ptolemy described as negligible for certain practical purposes (*Harm.* 1.16, p. 39.19-22; 40.1-6; Hagel 2009, 184-85).

On the basis of either of the described algorithms, the computer can readily establish optimal extensions for either a single pipe or a pair simply by comparing the results for various values that are separated by small steps (e.g., 0.1 mm), throughout the conceivable overall range. For a pair, the results are conveniently visualised as a coloured Cartesian plane, where different shades indicate different numbers of near-pure intervals, or also as a 3D surface, where the optimum stands out as the tallest peak (Fig. 9). Where the upper ends of both instruments survive, meaningful results are expected to include similar lengths for both reeds and therefore an optimum close to the diagonal $x=y$ in the diagram.

Optimisation in this sense thus establishes a maximum by varying one specific parameter on which all members of the result set (the predicted pitches) depend.

5. Misapplying the concepts

It might go without saying that the success of the method relies on varying the right parameter across a meaningful spectrum. A reed of 30 cm length would make no sense – but the computer would not know that. Neither would it make sense to tamper with the evidence, for instance, by varying the positions of fingerholes (unless, perhaps, in order to produce an educated guess when a hole position is unknown due to damage). Producing a higher number of nice intervals is therefore not necessarily a token of better methodology; it may be quite the contrary.

An obvious example would be increasing the threshold value for admitting intervals. This would spawn new ‘near-pure’ intervals quite liberally, none of which would carry any real meaning. For instance, if the threshold is set to a semitone, i.e. five times the value I have generally been using, then a pair of notes spanning the obviously dissonant interval of a tritone would pass as a pure fourth. Even more absurdly, it might at the same time count as a pure fifth as well. When spelt out in a clear-cut way, the preposterousness of such an approach stands out so evidently that the reader may wonder why I would waste their precious time discussing the theoretical possibility of such outlandish fabrications. But what if these, instead of laying bare their misrepresentation of reality and common sense, came clad in smug technical language? Such as, «by increasing Hagel's unrealistically small admittance threshold, which in reality even falls short of the ranges associated with experimentally ascertained embouchure variation in double-reed instruments, our enhanced approach to virtually modelling the harmonicity of *aulos* finds was able to discover no less than 11 hitherto undetected potential pure intervals, taking our understanding of ancient music to a new level».

How many readers and even reviewers would not swallow this without raising an eyebrow? Note that all the facts are correct: embouchure variation can indeed change the pitch of a fingerhole significantly (though much less so for bass notes), and this consideration might well be technically implemented as an increased threshold, which would correctly increase the resulting numbers. Even so, a sum of truisms does not necessarily make a conclusive argument. In fact, the fictitious «enhanced approach» above basically abandons researching the properties of the actual instrument under scrutiny. Instead, it models the options of playing that instrument *against* its built-in musical properties. Undeniably, it is indeed possible to elicit the «undetected pure intervals» by adjusting the reeds in various different ways. Ultimately, it may well be possible even to play, from the same pair of fingerholes between the two pipes, once a fourth and once a fifth. However, this is trivial. The same could be argued for reed instruments of the modern Western orchestra. Nonetheless, we know that these modern instruments are carefully manufactured to play particular pitches, and there is good reason to assume that the same was true for many ancient instruments.

Unfortunately, the preceding is no mere fiction. The same logical error forms the basis of a recent publication (Bakogiannis *et al.* 2020), in which the authors sent the computer through five million iterations each of various algorithms only to establish what anybody equipped with a sketch of the Louvre *aulos* scale (Louvre inv. E10962; Bélis 1984; Hagel 2004, 2014) can work out: if all the notes would come close enough to a 'Pythagorean' tuning, one would count precisely 56 pure intervals. That is just the way a diatonic scale works; all one needs to know is that one pipe ranges from *A* to *a*, and the other from *A* to *d'* but lacks *B*.

The cited study also presents methodological issues in other respects. Its software (ENTROTUNER) relies on two types of input, fundamental frequencies and instrumental sound spectra. Instead of physically modelling the former, the authors use published values (53190), apparently without noticing that these do not represent the required fundamental frequencies but already take the predicted inharmonicity of higher partials into account (Hagel 2004, 380).

A sound spectrum, on the other hand, can only be obtained from a replica, with all the uncertainties associated with the reed and not least the playing technique. The authors multiply the problem by recording not a replica of the narrow wooden instrument with a small reed under scrutiny (which would have been available to them through their cooperation with renowned music archaeologist Chrēstos Terzēs), but a bone instrument with a wide bore and huge reed blades that produces a fairly different sound, and do not even compare the resulting data with the available published spectrum of a Louvre replica (Hagel 2004, 387 Diagram 1). Finally, the bone instrument is also used in a final experiment that shows how a musician can reproduce 'optimised' pitches on a replica.

I have deemed it necessary to dwell on a particularly flawed example because all this has huge bearings on our understanding of ancient music. Bakogiannis *et al.* claim to have achieved «the re-determination of the musical scales and a more in-depth understanding of the musicological aspects of an era» (53194). Actually, they have but enforced their preconceptions of how a scale must work upon an ancient artefact. All ancient authors, in contrast, agree that the true scales of antiquity by no means followed the principle of maximal 'harmonicity' at all costs. Not some but all of the contemporary lyre tunings so meticulously reported by none less than Claudius Ptolemy (*Harm.* 2.15-16) stand in stark opposition to the 'Pythagorean' scale implied by Bakogiannis *et al.*

Those ancient scales feature different kinds of (mostly smaller) semitones, which disrupt tuning sequences that rely exclusively on pure fourths and fifths. If an ancient *aulos* were built to play in tune with a cithara of Ptolemy's cultural environment, it would likely reflect such different fine tunings. There might be a reasonable chance to detect these using the method I have employed in previous studies, even though it relies on a *general* importance of pure fifths and fourths (see e.g. Hagel 2009, 353 on potential links between such a 'deviant' note and the musical documents of the period). Contrarily, a procedure that instates harmonicity where the instrument design does not bear it out would *a priori* override the intentions of ancient makers and musicians.

To be sure, it is perfectly possible that some non-pure intervals in the calculations depend on shortcomings in the formulae (less likely), measurements errors (more likely), or original design flaws rather than genuine musical intention. Also, ancient performers would certainly have tried to compensate for such shortcomings. It is absolutely reasonable to point out that this might have been the case, and to which extent each pitch would need to be bent. Only, one needs to keep in mind that such speculations cannot possibly bring us any closer to deciphering the intentions of ancient musicians than does the study of the physical properties of the artefacts in combination with literary testimonies and the evidence from the remains of ancient tunes.

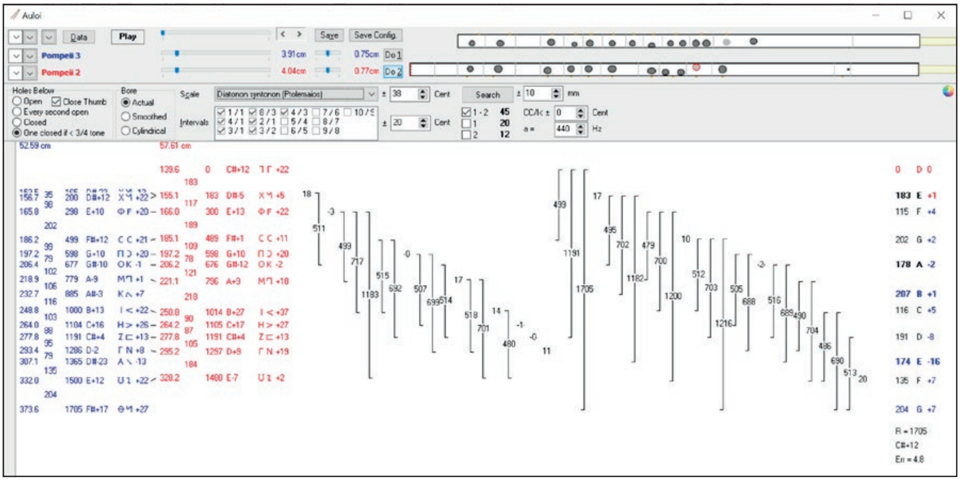

Fig. 10 – The data from Fig. 1 optimised for closed thumb holes. Image Stefan Hagel.

6. A small step forward

All this is by no means to say that the method I have followed cannot be improved upon. On the contrary, I would like to conclude by addressing an inaccuracy I had previously been sluggish enough to accept, but which I take this opportunity to eliminate. Above, we have come across the difference between 'open' and 'closed' playing: when the finger holes below the 'sounded' hole are closed, the note becomes just a tiny little bit lower (the effect is much more pronounced on most modern instruments, whose fingerholes are smaller in respect to the bore). Generally I have found that the open variant produces better results and therefore published these (with required modifications on instruments with a more chromatic design, where part of the holes was mechanically closed in any performance setup).

However, this misrepresents the physiology in the case of the thumbhole. When 'sounding' its note, the thumbhole is of course opened, by rolling the thumb on its tip, which then supports the instrument. However, whenever the index finger hole above it is released, it would be entirely unpractical to keep the thumb hole open as well; instead, the thumb naturally ensures a securer grip on the pipe by rolling back over its hole (where the makers sometimes carved an extra recess for it to rest in). As a consequence, an open-holes-below approach must be expected to misrepresent the pitch of the index finger hole, for which we need to reckon with at least one closed hole below. Apart from the index hole, no other hole is of course affected (unless in the case of *auloi* with more than one thumbhole, none of which are yet published).

After adjusting the software accordingly, the computer-optimised configuration changes from that shown in Fig. 1 to that of Fig. 10. The differences are minute, but it may be significant that they point in the direction of better tuning. In terms of near-pure intervals up to 20 cents deviation, we now obtain 45+20+12 instead of 43+19+12. Most strikingly, the top interval on the higher pipe has shrunk from 217 cents to 204 cents, precisely the whole tone ancient theory requires here (in the Lydian *tónos*, which is the central key of the ancient system and one of the keys the instrument could play, this interval marks the distance between *nḗtē synēmménōn* and *nḗtē diezeugménōn*, respectively a fourth and a fifth above *mésē*). One might also note that the difference in effective reed lengths has shrunk from 2 mm to 1.3 mm; but this is hardly of practical relevance.

What about the other published many-holed instruments? On the Louvre *aulos*, the adjustment for closed thumbholes produces one additional near-pure interval between the pipes, though this comes at the comparatively lower cost of losing one within the higher pipe; here, as well, the top interval shrinks from predicted 213 to 206 cents, almost precisely a whole tone. The Berlin *aulos* also gains one near-pure interval, from 18+9+3 (with reeds of 24.0 mm and 36 mm, which already contains an improvement over the originally published 16+7+4) to 19+8+4 (reeds: 24.5 mm; 35.5 mm).

Such a general tendency towards 'better' harmonicity when correcting measurements (Hagel 2012, 105 and 110, fig. 1) or refining the modelling of instrument physics and practicalities of playing raises confidence in the scientific method and indeed substantiates the validity of the approach. The prerequisite for this is that none of the adjustments are made precisely in order to fit the hypothesis. It is a pity that modern technology has not only given us unprecedented tools to advance all fields of enquiry in revolutionary ways, but makes it increasingly difficult to tell their proper and fruitful application from biased and redundant misuse. A relatively young and notoriously interdisciplinary field like music-archaeology is perhaps especially vulnerable in this respect – but the promise of recovering even a distant ringing of humanity's musical past is certainly worth the effort of keeping an alert eye on the technological demons that so easily subvert the intentions of their masters.

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ABSTRACT

Music-archaeology can show exemplarily the potential as well as the dangers of digital approaches. Both are here illustrated using case studies from the field of virtual modelling the intended scales of ancient reed instruments, with a focus on the requirement of the closest possible collaboration between music-archaeologists and programmers from the planning stages of a project and throughout its development. On the one hand, the potential robustness of predictive algorithms is shown, on the other, methodological fallacies are exposed that have led to redundant results and consequently misguided interpretations, which however, due to the ubiquitous partition of expertise, have slipped through reviewing processes. Finally, the author amends a problematic detail in the approach underlying previous publications of his own, showing how reflecting the physiology of *aulos* playing more accurately may enhance the harmonicity of modelled pitch sets, which in turn lends further credibility to the general method.