Stefan Hagel

‘Coptic lutes’ scales – finding a robust approach

Many years ago, in the blessed realm of Michaelstein, Ricardo Eichmann and I came to discuss the question of a possible relation between the fret placements on the late antique lutes he had studied and published with such admirable diligence,[1] on the one hand, and the tuning mathematically derived, aesthetically evaluated, and named *diatonikón homalón* by Claudius Ptolemy, on the other. We also wondered how best to assess the plausible meaning of observed fret positions when the crucial parameter of the location of the bridge cannot be ascertained, a problem that was analogous to one I had been dealing with. I promised to ponder both questions. Almost a score of years later, here is an attempt to settle the second part of my debt.

The pitches of fretted lutes are defined by string material, thickness, tension and the length of the resonating part of the string, between the bridge at the lower end (which may be incorporated in the string holder), and either the nut or a fret at the upper end, depending on whether a string is played open or stopped at some position. In the latter case, pressing the string against the fret will slightly raise the tension. In the lutes under scrutiny, the distance of potential fret positions from the nut can often be assessed with some precision, while that of the bridge can be estimated only very roughly. Therefore, a musical interpretation requires establishing the musically most plausible bridge position. Everything thus depends on a meaningful criterion what ‘musically plausible’ may mean for the culture in question. Based on the available evidence, this is generally taken to comprise a number of resonant intervals such as pure fourths, fifths and octaves; this may be extended to include pentatonic or heptatonic structures attested for historically and/or geographically related cultures, or even their implementation at particular absolute pitches. Ricardo’s results have proven the potential of this approach; so has my analogous research on doublepipes, where fingerholes and reed ends take on the roles of frets and bridges.[2]

Without some programming, however, the search for an optimal configuration is hampered by the number of calculations that each considered setting entails, as well as the complexity of these when moving from rules of thumb to algorithms that are more precise. This article contributes to overcoming such restrictions. Ricardo has developed his proposals by

[1] Eichmann 1994; Eichmann 1999; Eichmann 2000; Eichmann 2002; Eichmann et al. 2012: 78–84.

[2] For optimised consonance counts growing with accuracy of data, cf. Hagel 2012; Hagel 2014; For detecting attested scales, also Hagel 2008; Hagel 2010; Hagel 2020; for pitch levels, also Hagel 2004; Hagel 2008.

tentatively assuming the existence of certain intervals between particular frets and showing how this will result in plausible structures overall, effectively reflecting Martin L. West's approach to aulos fingerholes.[3] On top, he has employed a common end correction in order to balance the effects of fingering. This method is clearly fruitful; but it remains sensitive to small errors in the data on which the selected primary interval depends. If these are distorted, or if the original instrument actually failed to bear out that particular interval with precision, the results for all other intervals will be affected, potentially sparking an accumulation of errors.

In a refined approach, we would want to perform calculations for all conceivable bridge positions in order to identify the optimal. In practice, this breaks down to moving the simulated bridge by minute amounts, down to tenths of millimetres. Potential optima can be automatically assessed, for instance, by counting resonant intervals within a certain error margin, and then subjected to a human mind knowledgeable about attested musical structures. Again, an analogous procedure has made it possible to decipher the remains of ancient doublepipes. There I used to work with error margins of 20 cents, accounting not only for imperfections of design and slightly inaccurate data, but also taking into account the flexible intonation of the double reed. For the more precisely defined notes of fretted lutes (problems in the data set aside), I have decided to settle on a closer range of only ±15 cents.

Apart from the musical postulates, it will here be assumed that bridges were straight and placed perpendicular to the frets. This is not only in broad accord with pictorial evidence; the early designs with two rows of frets would never require such small adjustments in bridge positions for strings of different flexibility as found on modern guitars. Where a single arrangement of frets spans the neck, a very slightly slanted bridge might however be meaningful.

Finally, performers needed to tune the strings relatively to each other. This could be done by unison or by consonance, setting either open strings or fingered notes in relation to each other. For automatic optimisation I have accepted unisons, fourths, fifths and octaves in all possible configurations, provided that the resulting pitches would fall within the physically possible range for a given string material. Most plausible, of course, are unisons or octaves whenever at least one fret is involved, and pure consonances between open strings.

String mathematics are much more straightforward than those of woodwind are. The relevant formulae are provided, for example, in French 2009: 114–117. However, there it is assumed that a string is pressed directly against a fret, while in reality it is pressed slightly below fret

[3] West 1992: 96–101; cf. Letters 1969.

level at a point a few millimetres next to it; we will therefore modify the formulae for greater precision. Let L be the distance between nut and bridge, h_n the height of the nut (and in good approximation that of the bridge), f and h_f the distance of the played fret from the nut and its height, f_{-1} and h_{f-1} the corresponding values for the fret above it (towards the nut), a the distance of the finger centre from the played fret, and p, how far the string is pressed beyond fret level, the effective length of the string will be increased, for the fret next to the nut or wherever

$$p \le \frac{(f - f_{-1} - a)\cdot(h_n - h_f + p)}{f - a},$$

to approximately (cf. Figure 1A)

$$L + \Delta L = \sqrt{(L-f)^2 + (h_n - h_f)^2} + \sqrt{p^2 + a^2} + \sqrt{(h_f - a)^2 + h_n{}^2}\ ,$$

and otherwise to (cf. Figure 1B)

$$L + \Delta L = \sqrt{(L-f)^2 + (h_n - h_f)^2} + \sqrt{p^2 + a^2} + \sqrt{f_{-1}{}^2 + (h_n - h_f)^2} + \sqrt{(f - a - f_{-1})^2 + p^2}\ .$$

The differences to French's straightforward formula (4.23) are of course small, but still worth taking into account; additionally, the refined formulae make it possible to assess the effect of tensing the strings even more by pressing them against the neck (p=h_f), causing a significant increase in pitch for taller frets.[4]

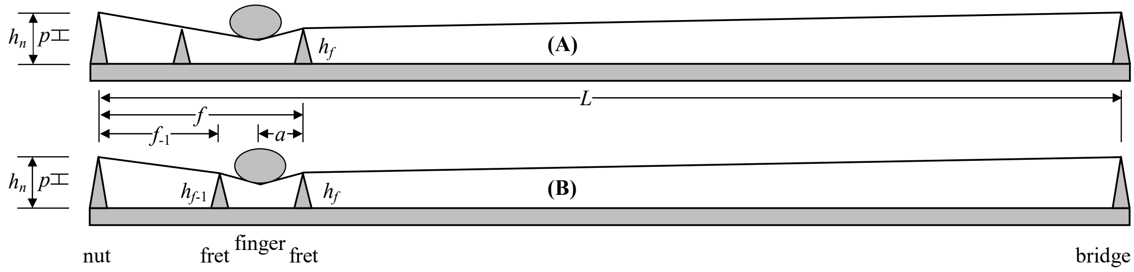

Figure 1: Schematic representation of a string pressed against a row of frets

In the following, I have set a to half the distance between adjacent frets but no more than 5 mm, and p to 1 mm, which should warrant clean tone production while not straining the player's fingers.

Another important factor is string tension – though it has limited effects as long as we are only investigating musical scales in terms of relative pitches. For the initial evaluation I will assume that the highest string was tuned about a third below breaking pitch, giving the instrument the most brilliant sound possible. Short-necked lutes, however, may use lower

[4] Note that this eliminates the distinction between 'theoretical' and 'practical' bridge position; those given here are to be understood as physical values.

tension, and the open strings of instruments with only two or three courses like those studied here would normally not exploit the entire useful pitch range. We must therefore reckon with absolute pitches well below the possible maximum.

We know that strings of different diameter were used for the differently pitched strings on ancient lyres, and in the early Middle Ages the diameters of lute strings were regarded as optimally reflecting the ratio of their pitch relation.[5] Therefore I follow the same rule here, starting from a typical diameter of 0.7 mm for the treble string and adjusting the others according to the respectively assumed intervals between them.[6]

Pitch is also determined by the string material. Throughout antiquity, the typically attested material is sheep gut, though silk strings cannot be ruled out from some point on.[7] Again, the difference in terms of relative pitches are small, though gut, a priori more plausible, seems also to yield better results. In absolute terms, however, silk strings would sound about a fourth higher.

It is a straightforward task to integrate all these factors within a computer program and connect it to a database with the various measurements. In addition, a useful research tool also requires an interface that makes all parameters easily accessible for experimentation, displays resulting pitches in real time, and compares these to known structures. Apart from mere descriptive values, such as frequencies in Hertz and interval sizes in cents, I have found it useful to display relevant consonances within the discussed threshold as well as modern and (approximate) ancient note names, including deviations in cents.

Antinoë

The early Byzantine lute from a female tomb in Antinoë forms the natural starting point for testing the method, as it is not only one of the best preserved instruments, but also the most extensively studied.[8] It features two distinct sets of frets, three for the leftmost string and six for the remaining two strings, whose spacing implies that they were played together as a double-string course;[9] for the present sake I will thus treat them as a single string. Surprisingly, the two rows of frets have no position in common, although the left middle and the right third lowest frets are relatively close.

When running through all possible configurations of bridge positions and relations between the strings, with gut strings and a treble string tuned a neutral third below breaking pitch, and

[5] John Philoponus, *in de An.* 15.373–4; Iḫwān aṣ-Ṣafāʾ *Ep.* 5.8, p. 113-113 Wright; *Kanz al-tuḥaf* 5, p. 178 Tsuge.
[6] Our results are thus in accord with Eichmann 1994: 65: “geschätzt maximal ca. 1 mm stark”.
[7] Eichmann 1994: 65.
[8] Friederich 1984; Eichmann 1994: 19–24; 70–78; Eichmann et al. 2012.
[9] Eichmann 1994: 69.

evaluating these in terms of resulting consonances, the computer suggests the arrangement shown in Figure 2, with vibrating string lengths of 387.5 mm.[10] First of all, it is encouraging to find the strings tuned in perfect fourths out of almost 200 theoretical possibilities, since this is not only the tuning predicted by Ricardo,[11] but has been the most typical, often exclusive, interval between adjacent strings of short-necked lutes from the earliest attested sources on.[12] Secondly, we encounter quite a number of excellent fourths and fifths, and the two possible octaves in such a setting are also very well in tune.

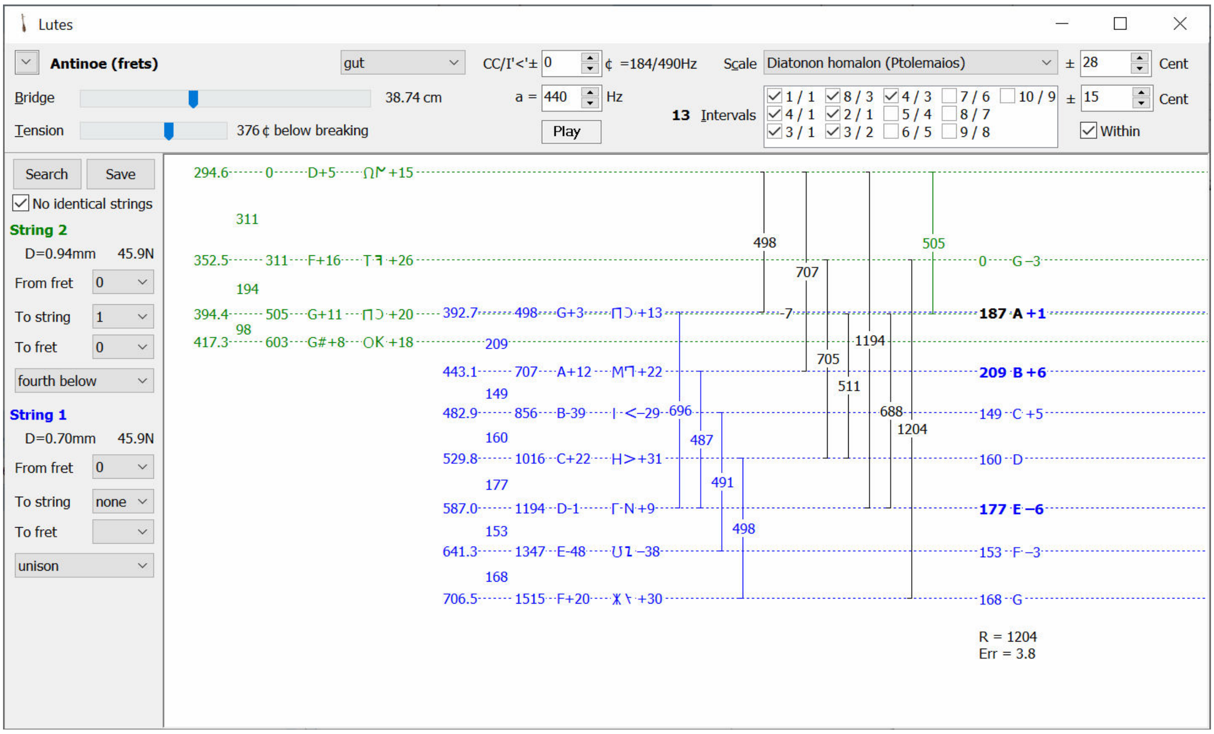

Figure 2: Calculated optimal configuration on the Antinoë lute for gut strings with treble a neutral third below breaking pitch

In this optimal model, the perfect fourth between the courses is established by ear; this option is perfectly plausible, as contemporary musicians were accustomed to tuning fourths on the lyre, where there is no fretboard to facilitate the task. On the other hand, we see that the left middle fret deviates from a pure fourth only by the thirtieth part of a tone, so it might as well be used for tuning by unison. In this case, we would arrive at the almost identical configuration shown in Figure 3, with the bridge pushed 3.5 mm downwards.

[10] This value is close to the mean (388.15 mm) of the two possible ranges deduced in Eichmann 1994: 70–78, i.e. 380.9–382.9 mm on the one hand, and 393.4–395.4 mm, on the other. Compare 384.2–386.2 mm in Eichmann et al. 2012: 78–82, as well as 380 mm used by musician Jean-Pierre Leroy-Dragon on a replica according to Eichmann 1994: 133.

[11] Eichmann 1994: 74.

[12] E.g. Al-Kindī, *Risāla fi ḫubr ta'līf al-alḥān* 1.

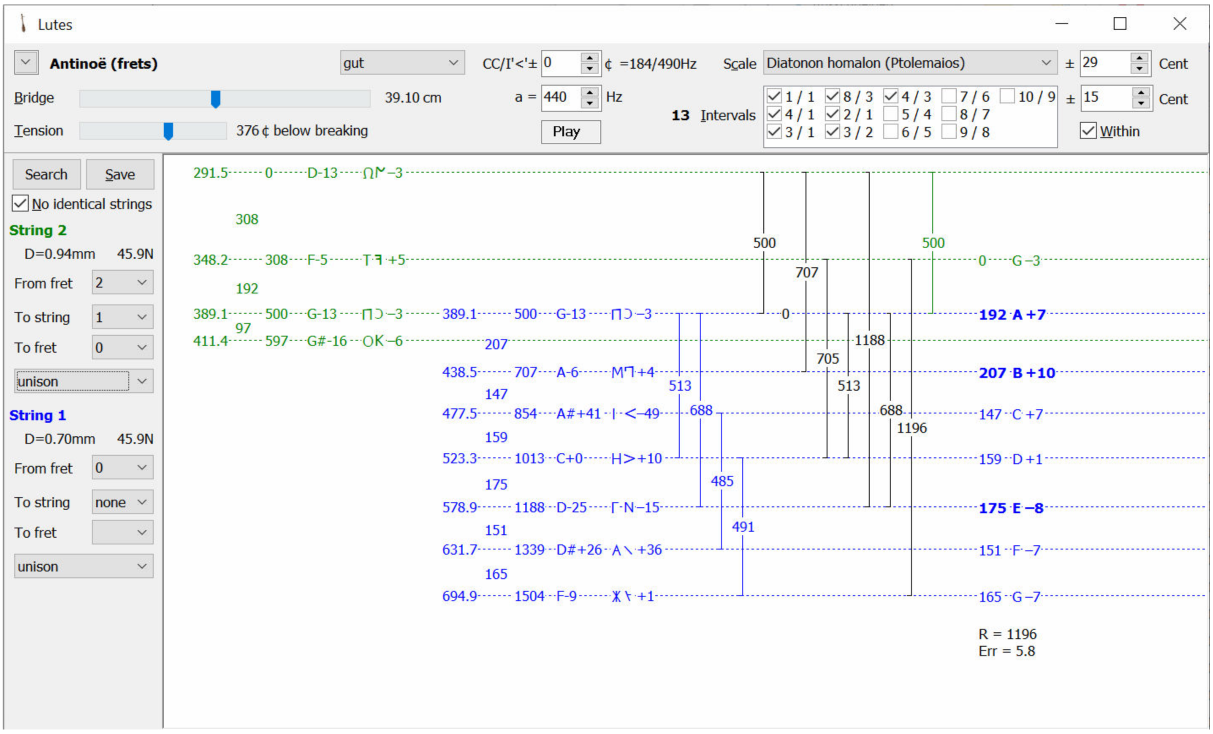

Figure 3: Optimal configuration on the Antinoë lute for gut strings with treble a neutral third below breaking pitch, tuning by fret

In his interpretation of the scale, Ricardo has pointed to the existence of both tone-like and three-quartertone-like intervals, with potential connections back to Ptolemy's 'even diatonic' in the second century CE and forward to Persian-Arabic scales with neutral thirds.[13] This heptatonic analysis is superbly borne out by the present re-evaluation. Above all, the calculated scale is practically indistinguishable from an octave composed of 'smooth diatonic' tetrachords according to Ptolemy's precepts.[14] In Figure 2, no note deviates more than 6 cents from the ideal pitch. This is not only true for the eight continuous pitches, but also for the bass note, which is separated from the second lowest by a minor third. As this stands 1194 cents below the note indicated, in relative pitch, as 'E–6', it is actually situated precisely an octave (1194+6=1200 cents) below relative 'E' and therefore represents exactly the ideal bass note of the scale.

In Ptolemy's work, the 'smooth diatonic' tetrachord division (*diatonikón homalón*) in interval ratios of 12:11 – 11:10 – 10:9 (ascending) is first and foremost a mathematical construction. Forming part of the set of possible superparticular divisions, it is not among those that Ptolemy could map to known lyre tunings of his time. However, he asserts that when being realised on his experimental instrument,

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[13] Eichmann 1994: 76–78.

[14] Note that such a scale is by no means a typical side effect of the algorithm used to establish an 'optimal' configuration – its orientation towards maximising fifths and fourths would contrarily favour the so-called 'Pythagorean' tuning (Ptolemy's *diatonikón ditoniaîon*).

> ξενικώτερον μέν πως καὶ ἀγροικότερον ἦθος καταφανήσεται, προσηνὲς δ᾽ ἄλλως καὶ μᾶλλον συγγυμναζόμενον ταῖς ἀκοαῖς. (Ptolemy, *Harmonics* 1.16, p. 38.30–32 Düring)
>
> it will exhibit a rather alien and rustic character, but otherwise gentle, and more so when the ear becomes trained to it.

Does Ptolemy's notion of rusticity betray his familiarity with similar musical structures, albeit not in the context of the Hellenistic concert hall? The tetrachord in question surfaces whenever a pure fourth on an instrument is divided into three steps of similar physical distance, be it lute frets or wind fingerholes. A further step of the same size on its upper end extends it to a pentachord, forming a whole tone of 9:8. Indeed equally spaced fingerholes are found in many musical cultures. Within Egypt, Ptolemy's primary geographical horizon, respective instruments are attested from Pharaonic up until modern times.

The Antinoë instrument may therefore belong to an age-old tradition of (partially) equidistant scales, for a while sidelined by Hellenistic music, but still strong enough to be aesthetically commended by a Greco-Egyptian scientist. Later, it will resurface on the lutes of Early Islamic authors, eventually to be codified as the backbone of *maqām rāst*. Importantly, the Antinoë instrument is an unequivocal witness that such a scale was not newly introduced from the East a few centuries later, but held firm ground right in a Roman-Imperial-founded Greek city (and Christian bishopric) in late antique Africa.

The relative scale we have derived proves largely independent of string tension, when the entire instrument is tuned down to lower pitch. However, from a certain point on, individual consonances deteriorate gradually. From general organology we might expect a tension in the range of about 25–42 N,[15] lower than the highest plausible configuration set out above. At the lower margin of that range, with a bass note of 220.5Hz, maximal deviation from 'smooth diatonic' still rises only to 8 cents, though a mere 9 consonances remain within the threshold of 15 cents, compared with 13 at the high limit.[16] However, the calculated configurations do not deteriorate between high and medium tension and are therefore of little help in assessing the instrument's intended absolute pitch.

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[15] Cf. Jahnel 1996: 230 fig. 171.

[16] Actually the number of consonances can be increased to 11 by tuning the bass string an octave below fret 4 from the nut on the treble strings (bass pitch 214.5Hz). This, however, distorts the corresponding scale, e.g. making the disjunctive tone 19 cents too wide.

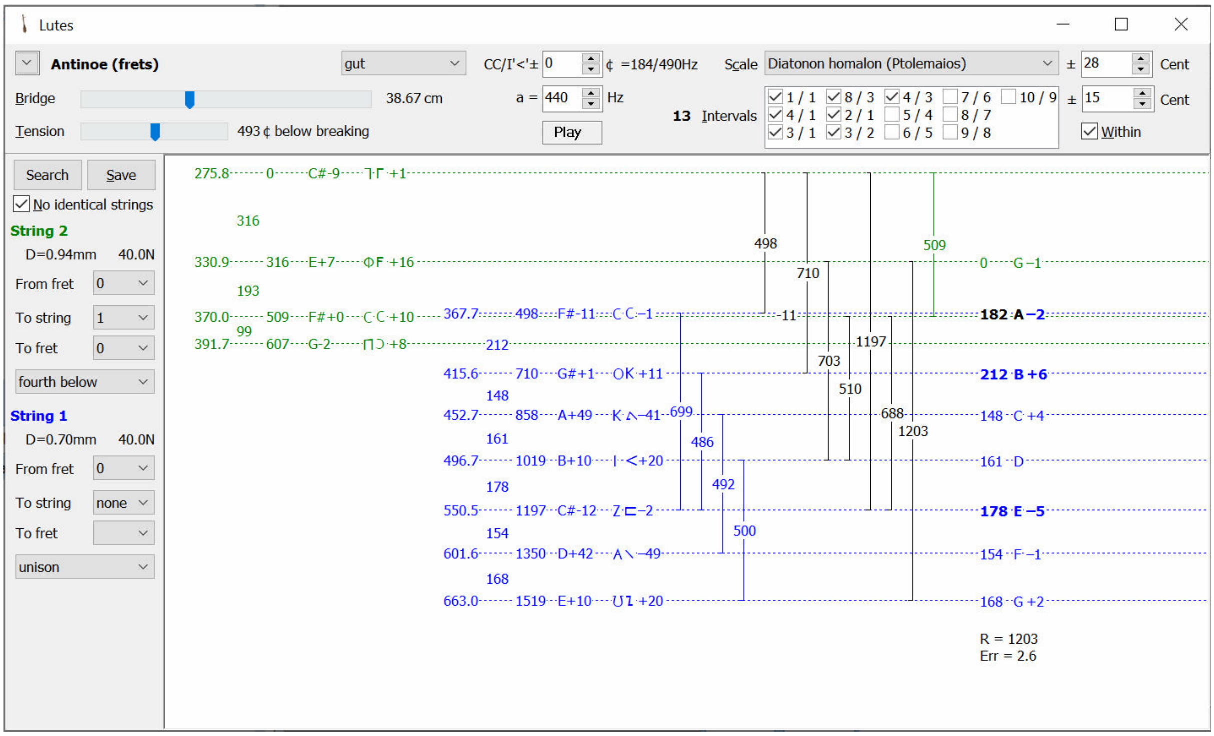

Figure 4: Optimal configuration on the Antinoë lute for gut strings with treble about a fourth below breaking pitch

Figure 4 gives a plausible example; while still remaining at the higher side regarding string tension and therefore brilliance of sound, it is oriented towards the pitch standard of ancient Hellenistic music by setting the lowest note of the higher strings one octave above the *hypátē* of the kithara, which originally was its lowest string and frequently served as the final note of melodies. Indeed the nature of the Antinoë lute, most of whose playable notes are higher than its open treble string, suggests that it would have played an octave above comparable instruments of the lyre family; consequently I have transposed the ancient notation signs in all diagrams accordingly (Lydian *mésē* thus corresponds to 490Hz instead of 245Hz). When tuned in this way, the Antinoë lute might also play together with the Louvre aulos, an instrument from unknown Egyptian provenance and date, whose lowest note also represents the lyre *hypátē*. However, such a duo would encounter limitations, since the lute divides the scale in near-equal intervals, while the Louvre aulos distinguishes sharply between tones and semitones. Nevertheless, one of the two might always provide a harmonic background for the other.

Whatever precise pitch is chosen, it is obvious that the structurally central ‘disjunctive’ whole tone occupies the interval between the open treble course and its first fret – just as the first fret of the later *ʿūd* is always positioned at a similar whole tone. As a consequence, the open treble string is labelled ‘A’ in the scale at the right hand of our figures, representing the functional *mésē* of ancient Greek theory, which is defined as forming the lower boundary of the disjunctive tone and understood by the theoretical sources as the centre of tonality. Notably, this is the only note available on both courses.[17]

The bass string appears to combine various possible functions in relation to the treble course. On the one hand, it was doubtlessly used for accompaniment in intervallic harmonies as seem to have been typical for ancient musics, being attested in cuneiform just as well as Greek sources. On the other, its highest fret provided a semitone above the open treble course, bisecting the whole tone. In terms of Greek theory, it thus enabled modulation of 'scale' (*kata sýstēma*), into a conjunct tetrachord – though not another 'smooth diatonic' tetrachord, but one distinguishing itself by a real semitone that could not be mistaken for the alternative whole tone. In terms of later Arabic writings, this fret provided the 'neighbour of the index' (*muğannab as-sabbābā*), a position much discussed by theorists.[18] The lowest bass-string fret, finally, stood precisely a small tone (10:9) below the open treble course, complementing its scale to an octave. Within the speculatively proposed pitch, furthermore, it would have formed a leading note to the open treble course that is commonly attested in the surviving melody fragments from ancient Greek music, and which is associated with the lowest cithara string, *hyperypátē* ("beyond the topmost").[19] The interpretation as a leading note, as opposed to that of the 'tonic' of the entire octave, gains plausibility from the stringing: while a single-course tonic at the bottom of a double-course melody would be musically most awkward, a resounding double-course final after a duller single-course leading note makes much sense. Does the lute design thus bear out the particular personality of this note, the cultural awareness of which we find so distinctly expressed in its name on the lyre?

In addition, the bass note of the proposed configuration would form a typical bass note of ancient Greek music, apparently related to typical pipe designs, where it also may stand below a gap in the scale, just as it does on the Antinoë lute.[20]

Finally, if the open treble course corresponds to cithara *hypátē*, the scale, defined by the disjunctive tone occupying the lowest position, would appear to be Hypodorian, in Ptolemy's reckoning. Within the 'Greek' pitching of Figure 4, this is correctly reflected in the Hypolydian key.[21] This tonality is excellently attested in late antique Egypt. It is found in many musical fragments from the period, including the single surviving Christian hymn, and

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[17] Compare the fact that structural *mésē* is the highest note available on both pipes on the Louvre and Berlin auloi.

[18] E.g. Al-Fārābī, *Kitāb al-mūsīqī al-kabīr* p. 512–513 Ḫašaba.

[19] Hagel 2016. Note that the notion of 'topmost' refers to the string's physical position, not the modern notion of 'high' pitch.

[20] Hagel 2009: 327–364.

[21] For the somewhat confusing relation between kithara tunings expressed as octave shapes and the ancient keys in which they were notated cf. Hagel 2009: 56–61.

appears obliquely indicated as the actual mode of a hymn composed by Synesius, only about a century before the Antinoë lute was interred.[22]

The present analysis of the lute scale as obeying basic tenets of Greek theory entails that its notes can be classified either as belonging to the skeleton of tetrachord-bounding ‘fixed’ notes or movable pitches in between. If it holds some truth, we would expect that the fret layout was conceived in two steps: only after the positions of the fixed notes are determined can the tetrachords be structured internally. The latter would most straightforwardly be done by dividing them into three stretches of equal length. Setting up the skeleton, in turn, may start with positioning a fret at a perfect fifth on the higher course; if both courses are fitted and tuned, this must also create a perfect octave with the bass note (in Figure 4, the note in question is only 3 cents off).[23] The first fret on the higher course, in turn, may be placed at a fifth from the bass note (8 cents off), and the third on the bass string, a fourth, or in unison with the treble course (11 cents off). After trisecting the distance between the two established treble frets (1.6 mm and 0.7 mm off), the lowest bass fret is naturally found at a fifth below the third treble fret (1 cent off). An octave above, the highest fret comes to be placed (2 cents off). The one below can be centred between its neighbours (0.0 mm off); finally, the semitone on the bass string may be established by bisecting the tone (0.2 mm off).[24]

Saqqāra

Space forbids discussing the incision marks on the Antinoë lute as well as most of the other lutes studied by Ricardo. I will finish with the Saqqāra instrument, whose treble fret marks make it almost a twin of the Antinoë lute. Since no traces of the bass frets have been determined, only the open string can be taken into account here. The automated optimisation nevertheless determines the suspected layout as optimal. Figure 5 once more gives the results with the absolute pitch of the treble course set an octave above the lyre *hypátē*. The bass string is optimally tuned an octave below the fourth fret of the treble course;[25] this also creates

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[22] Pöhlmann/West 2001 nos. 43, 44|, 45a, 45b, 48b, 49b, 59. Synesius, Hymn 7.1–3: Ὑπὸ Δώριον ἁρμογὰν / ἐλεφαντοδέτων μίτων / στασῶ λιγυρὰν ὄπα… “To Dorian tuning / of ivory-bound threads / I will raise my voice clearly…”. The reader or listener must first understand ‘*hypodṓrion harmogán*’, “a Hypodorian tuning”, which needs later to be rescanned to identically written and sounding ‘*hypo dṓrion harmogán*’ “accompanied by a Dorian tuning”. The philosopher’s pun combines the ‘Dorian’ of supreme Platonic pedigree with the Hypodorian he probably actually employed on his lyre. With the highest fret of the bass string as an alternative to the lowest fret of the treble course, the Antinoë lute would modulate to Dorian tuning.

[23] Cf. Eichmann et al. 2012: 82.

[24] Trisection as postulated here combines, so to say, the two approaches outlined in Eichmann 1994: 72–77. The resulting lowest distance is however 1.6 mm wider than a third of the overall distance; interestingly, it thus appears more accurate from a musical viewpoint.

[25] In Eichmann 1999: 514, this is expressed as a general rule.

a perfect fifth and an excellent fourth between the courses as well as excellent melodic intervals and a stupendously well-tuned ‘smooth diatonic’ scale. The fifth with the nut, from the definition of which Ricardo’s reconstruction proceeded, deviates by merely 3 cents, so that his predicted physical bridge position of 378.5–380.5 mm accords well with the machine-optimised 380.6 mm, which in turn lies comfortably within the plausible bridge traces found at 375–395 mm.[26]

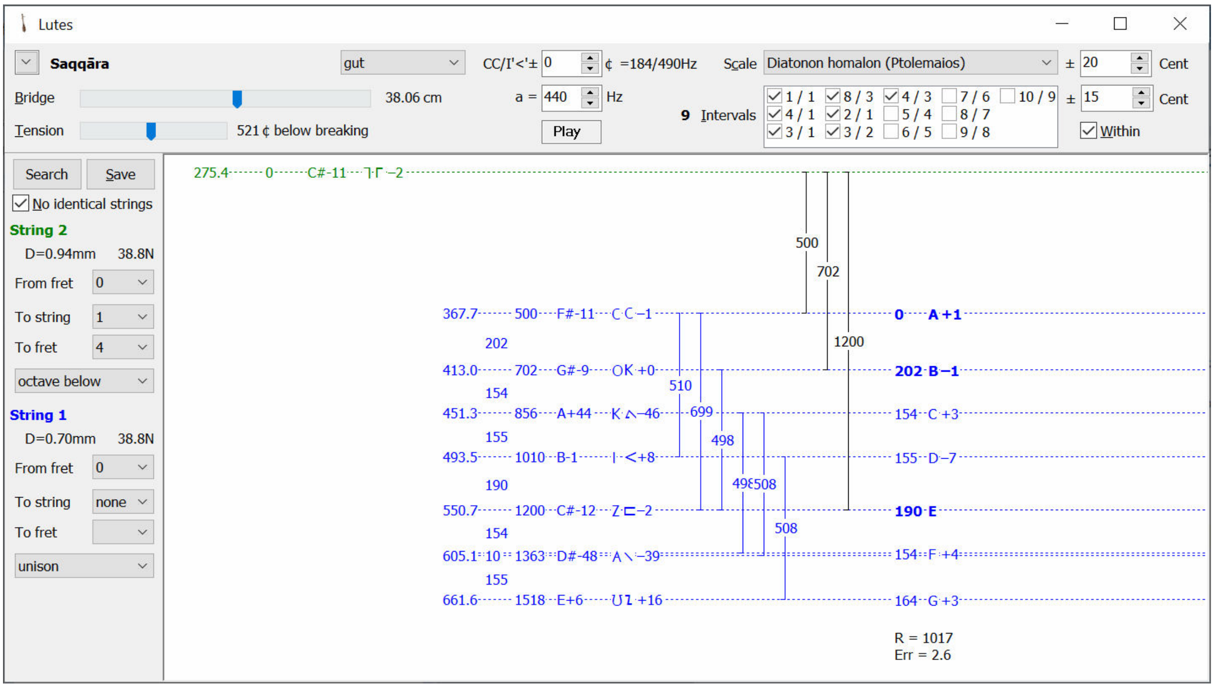

Figure 5: Optimal configuration on the Saqqāra lute for gut strings hypothetically tuned to the ancient pitch standard

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