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J.H. Lambert's Scientific Tool Kit. Exemplified by Lambert's Measurement of Humidity (1769–1772)

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*With these four questions originate four sciences, that the human intellect has to use as just as many means and tools, if he wants, with conscience, recognize the truth as true, present it as true, and discern it from error and appearance. (Lambert 1764, I, X)<sup>1</sup>*

## **Introduction**

In 1769 Johann Heinrich Lambert (1728–1777) devoted a long essay to the measurement of humidity and the construction, fine-tuning and ‘synchronisation’ of a measuring instrument, the hygrometer (Lambert 1769). In 1772 a second essay appeared that reported, processed and analyzed the results obtained by various persons with this experimental set-up (Lambert 1772).

Why should this fragment of the early history of meteorology be the subject of this paper and be of interest to historians and philosophers of science today? For one, it is an unusually well-documented case of late 18th century experiments, with richly detailed essays from Lambert's hand, and an extant correspondance between Lambert, the instrument-maker Georg Friedrich Brander (1713–1783), and co-workers collecting the data from the hygrometers. As such, this case provides various insights into the process of setting up experiments, the material construction of the instrument, into making the experimental results communicable between experimentators and organising scientific data-gathering. As such, Lambert's experimental work is an important and particularly enlightening link between Newtonian experimentalism of the early 18th century and the organized laboratory experiments of the 19th century.

However, the main goal of this paper is to detail Lambert's views on scientific practice that inform the cluster of questions on humidity. In 1764 Lambert had published what is considered his main philosophical work, *Neues Organon* (Lambert 1764), followed in 1765 by the *Anlage zur Architectonic* (Lambert 1771a) that was published only in 1771. In these works, comprising near two-thousand pages, Lambert lays out his scientific views, discusses his way of proceeding in tackling scientific problems, presents heuristic methods and little tricks to overcome difficulties etc. These ideas represent the outcome of many years of reading and scientific practice, and continued to guide Lambert in his later scientific work, as, e.g., hygrometry.<sup>2</sup>

## **The context of Lambert's work on hygrometry**

Looking at the publications on the measurement of air humidity during the 18th century, it

is immediately apparent that between the years 1760 and 1790 the topic was a popular one. At both sides of the Canal many essays and books appeared discussing the construction of a hygrometer and the design of a scale for measuring humidity.<sup>3</sup> The study of humidity was part of a more general interest in all things pertaining to the weather. In the 18th century, meteorology, the study of the weather, held an appeal for many researchers, because it had connections with many other sciences (physics, chemistry, electricity, ...) (Feldman 1990, 143–144), and seemed particularly amenable to quantitative observations and measurements, preparing the ground for laws that could be mathematically expressed. In particular, meteorologists were among the first in designing precise instruments for experimental physics (Feldman 1990, 145). Lambert's work on hygrometry is deeply embedded in this context and subscribes to all characteristics of a late 18th century physics which Feldman has baptized 'exact experimental physics'.<sup>4</sup> Lambert's main source and influence in hygrometry was Petrus Musschenbroek, under whom he had studied in Leiden (1757–58).

Thanks to Lambert's and de Saussure's work in the 1770ies and 1780ies Dalton's law of partial pressures was formulated for the special case of aqueous vapor: "the total pressure of moist air at a given temperature is the sum of the pressures of its components, water vapor and dry air" (Feldman1990, 175).

### **Lambert's Mode of Proceeding**

In the last section of the *Neues Organon*, called *Dianoiologie* or the Doctrine of the Laws of Thought, Lambert gives a detailed account of his *modus procedendi* in things scientific (Lambert 1764, I, 386–450). In his letters, a more succinct overview of the same procedure is described:

1. [I write] down everything that comes to mind regarding a certain topic in short propositions, namely in the order in which they come to my mind, may the propositions be trivial, hypothetical, doubtful or even partly contradictory
2. I pursue this until I see something can be done with it
3. I then look whether (partially) contradicting propositions can be reconciled by further determination and restriction, or whether it is unclear if they should be kept just like that for the moment being
4. I look whether this collection of propositions belong to one or more aggregates
5. I compare the propositions, to see whether they depend from each other, what premisses the others entail, and I start numerating them
6. I look if the first propositions are clear or if they need something extra to be clearly determined
7. and I search for what is needed to connect the first propositions to the others
8. I reflect on what I have so far and I look whether there is a gap in the system or whether there lacks a part
9. especially I reflect to find the purposes of this whole system and to see if I need more to find this out.

Once this last stage is reached, Lambert starts to write things up in a publishable form, partly inverting the order of invention into an order of exposition:

10. I start writing on the topic beginning from these purposes, because it makes clear from what angle I look upon it
11. Then I show how I get at the concepts that are basic to the thing, and why I

neither expand these concepts nor restrict them any more than I do

12. Finally, I try to clarify the many meanings present in words and figures of speech, and to keep them that way; that is, I try to use them not as subjects but only as predicates, because the meaning of the predicate is determined by the meaning of the subject. (Lambert 1781-1787, I, 345–346 )<sup>5</sup>

This near algorithmic scheme of invention and exposition is modulated according to the kind of investigations at hand. As Lambert notices in some fragments of the logical and philosophical *Nachlass*:

The routine (procedure) can be very different. Wolff liked to abstract. Baumgarten tried to apply abstract concepts to genera, to find new genera. Meier used his topic. Euler calculates. Dan. Bernoulli likes to use pictures as an aid. Muschenbroeck experiments without a theory. Others like to assume hypotheses. Everyone has his favourite guideline. (Lambert 1782 & 1787, I, 406–7 )<sup>6</sup>

All these subroutines, partly taken from other scientists, partly self-developed, are discussed in Lambert's *Neues Organon* resp. *Architectonic* resp. explicated in one of his other writings. In particular, Lambert had written an *Organon* for 'exact experimental physics', an *Organon quantorum* which was included as the fourth part of the *Anlage zur Architectonic* "Die Größe" (Arch. §679– §923).<sup>7</sup>

In the case at hand, hygrometry, Lambert's *modus procedendi* is implemented on various different levels, each of these levels requiring specifics and details not provided for in this general outline. We will, somewhat artificially, discern these levels, and discuss them accordingly to Lambert's mode of proceeding. A first level is that of questions. Lambert had written in the preface to his *Neues Organon* (Lambert 1764, I, VII) that a theory of questions is as important as a theory of propositions (see also Dian. §423–550).

### Coming to questions

Asking the right questions when setting up and performing experiments is not a trivial task. Upon his becoming member of the Berlin Academy, Class of Experimental Physics, Lambert described the problem in the following words:

Purposeful experiments in chosen circumstances are problems that we propose to Nature. [...] She responds with precision, not to what we think we ask, but to what we actually ask. To avoid being deluded and waiting for nothing, one has to rigorously make sure that the conditions imposed by the problem are known, so that one is able to chose the circumstances and to adapt the experiment to these conditions. (Lambert 1765/1767a, 508)<sup>8</sup>

The question of what constitutes a 'good' experimental question is for Lambert intimately related to mechanism and mathematics.

Experimental physics is absolutely necessary in cases where there is no way to see the mechanism by which Nature operates [...] one can add calculation, one can apply the principles of mechanics where this mechanism is pronounced enough to be seen or simple enough to be conceived of. (Lambert, 1765/1767a, 509)<sup>9</sup>

The translation of the observed 'mechanism' (what constitutes mechanism will be discussed in the next paragraph) into mathematical language ties experimental physics up with mathematics, both being indispensable for the development of the other and functioning as check mechanisms, one for the other:

Calculation brings in precision and generality. Experiment (Experience) verifies

both and discovers each circumstance omitted or falsely admitted. Neglecting calculation and the theory one performs arbitrary and aimless experiments. Neglecting experiments one is in danger of running into chimeras and of producing calculations that apply in every other world but this one. (Lambert, 1765/1767a, 509)<sup>10</sup>

Lambert's use of the word 'mechanism' might seem curious, but it should be interpreted neither as an avowal of a pure mechanical world view, nor as a shallow metaphor. It is rooted in the observation that all machines have periodic behaviour (Arch. §332). On other occasions, Lambert also uses the word 'rules' ("Regeln") to indicate this same relationship between observable behaviour and underlying regularities. In its most general form, Lambert's basic scientific research principle can be formulated as follows:

If a thing is given that is made after certain rules, to find the rules after which it was made or could have been made.<sup>11</sup>

It should, however, be remarked that in Lambert's view phenomena that obey 'rules' or 'mechanisms' are only one class of natural phenomena. Another class contain those that are generated by laws ("gesetzmässig"), yet another class those that are or appear random ("zufällig"). As this last category makes very clear, Lambert's classes are phenomenological categories, indicating the knowledge of the investigating subject about the object of investigation.

Lambert largely expounds upon these categories in his *Architectonic* (Arch. §307–350). They are mainly heuristic categories, i.e., given a set of (quantitative) data obtained during a stretch of time, how can find the rule or law that governs the order or non-order of this data set? If the set appears random, it can be a series of random events, or a series generated by a law. If, however, the set is ordered, i.e., there are similarities or repetitions between adjacent data, the set can be generated by a rule, by a mechanism. Lambert calls this last class of local order and considers it to be the most tractable set of problems in Nature, as expressed in the quote above.<sup>12</sup>

A sure sign of such local order is periodicity (Arch. §327). Hence, to start an investigation into the laws of Nature, to start a new discipline, one should focus on periodic phenomena first, try to derive their rules and then gradually expand the theory. This is exactly Lambert's purpose in meteorology:

It seems to me that if one wants to make meteorology more scientific than it currently is, one should imitate the astronomers who began with establishing general laws and middle movements without bothering too much with details first. [...] Should one not do the same in meteorology? It is a sure fact that meteorology has general laws and that it contains a great number of periodic phenomena. But we can but scarcely guess these latter. Only few observations have been made so far, and between these one cannot find connections. (Lambert 1771b, 60)<sup>13</sup>

To obtain more data from various places Lambert proposed to set up a network of weather stations around the world, in which the various weather configurations (rain, clouds, dry ...) would be recorded with the use of a simple and small set of iconic signs, the ones still used nowadays in the weather report.<sup>14</sup>

An epistemological observation on Lambert's concept of periodicity is due. It has been remarked that one of the differences between 18th and 19th century physics was that the 18th century looked for correlations, whereas the 19th century looked for laws and causes (Feldman 1990, 175–177). This matches up with Foucault's analysis in *Les mots et les choses*, where a discontinuity in the representation of knowledge is described, going from classification and an ordering device based on similarities towards structures and

derivational order (Foucault 1966). Lambert's periodicity seems to be an intermediate concept, turning correlations slowly into laws, turning the similarities into quantitative series, in which structures and dependencies can be tracked down (as his three categories of order indicate rather explicitly). This is not an isolated case. In mathematics, periods and periodicity played a similar role around 1800 to turn a data-driven number theory into a modern theory of structures in the hands of Gauss and others.<sup>15</sup>

### **What is humidity?**

Lambert's essay on hygrometry starts off in exactly the order described in his *modus procedendi*, points 11 to 13 of presenting his ideas and theory. They behave, of course, inversely to his points 1 to 10 of getting at the heart of the matter. The main question to be solved in Lambert's introductory part is to determine what humidity really is, what other phenomena act upon on it, and how these can be put into a quantitative form.

As put forward in his points 12 and 13, Lambert starts by considering the word 'humidity' in all its significations and figures of speech, as they can be found in a dictionary. This way, Lambert connects to the common understanding of a phenomenon, as it appears in everyday conversation, and can, starting from there, gradually specify the phenomenon as appearing in his scientific research.

It is not necessary to explain what humidity is. One has only to pass through the fog to perceive it; because this is a kind of humidity immediately accessible to eyeview and sense of touch. One can also see it in the exhalations of boiling fluids. It also becomes visible in the Winter, when it attaches itself to windows or covers objects exposed to vaporous air, or, finally, when it appears as dew that covers the hairy surface of plants with an infinity of small drops. If in the Winter one transports the cold into heated rooms it attaches itself to glass or metallic bodies. This is known to everybody. (Lambert 1769, 69)<sup>16</sup>

Especially the phenomena where humidity can be seen or felt are emphasized, as a way of linking up non-scientific, everyday experience with guided scientific experimenting.

Lambert conceived of language as an 'archive of concepts' ("Behältnis der Begriffe"), ready to be used and developed. The goal of semiotics is to "reduce the theory of things to the theory of signs" (Sem. §23-24), or put differently, to adjust and control the mapping between the elements of the real world ("Realwelt") and the intellectual world ("Intellektualwelt"). Because everyday language has much that is 'hypothetical' or 'arbitrary' ("hypothetisch"; "willkürlich") – one could say in modern terms, language has much redundancy (on the semantic level) – one needs procedures to adjust this mapping when words are needed for specific, scientific discourses (Sem., §329-351).<sup>17</sup> For Lambert, a scientific discourse is more amenable to quantification than everyday speech and specifically should be 'designed' to avoid endless discussion and polemic ("Wortstreit", "logomachia"). Therefore, scientific concepts ("Begriffe") should be developed so that they are clear, understandable, but also fit for further refinement, either narrowing down its content or broadening it ("den Begriffsumfang bestimmen"). This way, Lambert hoped to avoid the endless definitions and repudiations of the Scholastics or of the Wolffian *Schulphilosophie* that hindered the progress of science. Lambert discerned two modes in which the process of determining the content of a concept could proceed: oscillatory or asymptotic (Arch. §561). The first mode is a series of consecutive definitions where the next definition contradicts the last one, the second mode of defining is the one Lambert wanted to establish in science, the determination of a concept with ever increasing precision and consensus. Such determination and/or adjustment is possible through the use of 'coefficients', i.e., the adjectives and adverbs that determine the substantives and verbs

(that act like variables) (Arch. §437).

These [concepts and qualities] are not simply put or thrown together, but are multiplied [with the coefficients, adjectives and adverbs], because the abstract concept acquires new qualities.<sup>18</sup>

Proceeding this way, from everyday words to gradually determined words, one can avoid to invent artificial words.<sup>19</sup>

This is exactly what Lambert does after introducing the concept ‘humidity’ by examples, it is determined further for scientific use:

The degree of humidity of air is the mass or better even the weight of all aqueous particles that float in a certain volume (e.g. in a cubic foot of air). *This is what the language of hygrometers should be reduced to.* (Lambert 1769, 69, my italics)<sup>20</sup>

Everything ambiguous that was possibly present in the word ‘humidity’ is thus equated with a definition that allows quantitative determination. This reduces the linguistic application range of humidity, but makes it amenable to the scientific language which is mathematics. Mathematics, or to be more exact: algebra, is for Lambert the characteristic language per se that can be best perfected so as to induce a proper mapping of the real into the intellectual world (Sem. §35).

As Lambert points out in his point 13, he tries to make his concept not a subject but a predicate, since the predicate is governed by the subject. This implies a further anatomy of the concept humidity.<sup>21</sup>

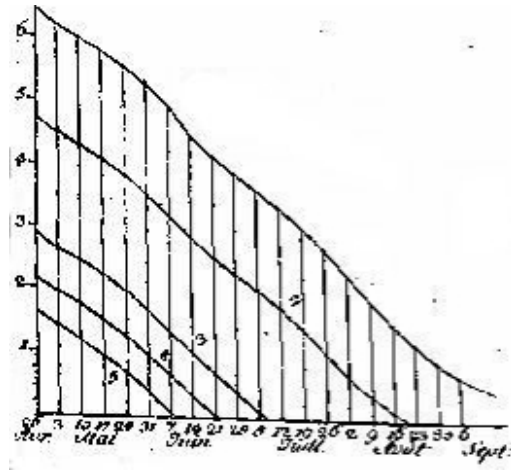
Let us try to track [humidity] in its major appearances that can be evaluated and measured. Let us begin to see it at the time of its birth. (Lambert 1769, 69)<sup>22</sup>

This leads to the investigation of evaporation, because evaporation causes the change of humidity. If one can ‘evaluate and measure’ evaporation, one will know humidity since it is governed by evaporation.

### **Evaporation: Experiments and Graphs**

Evaporation had been experimentally researched by the Dutch professor Petrus Musschenbroek in the course of his research on capillary forces (Pater 1979, 227–290). He had derived a correlation between the amount of evaporation and the total mass of water (not only the surface), these being in inverse proportion. Lambert’s first scientific publication in the *Acta Helvetica* (1755) repeated Musschenbroek’s experiments, because it was not clear whether Musschenbroek had taken into account all circumstances that entered into the problem and whether Musschenbroek had described the circumstances of the experiments with due detail (Lambert 1769, 70). Lambert’s results did not completely agree with Musschenbroek’s conclusions, but it was only some years later, Lambert having differed to settle the matter, that the Swede Wallerius “with much care” did similar experiments but came to the conclusion that evaporation correlates with the surface of the water only, and with the temperature and wind. Lambert concludes: “the cause of evaporation [lies] in the contiguity of air and water” (Lambert 1769, 72).

To settle if either Musschenbroek’s hypothesis or Wallerius’s was right (point 3), Lambert repeated the experiment in his own chamber (in three different set-ups), detailing the conditions of the experiment, even noting if he left his window open or not (which Lambert did in August, because it was too hot). His results confirmed Wallerius (Lambert 1769, 76 and 85).



**Figure 1:** Lambert's visualization of the evaporation experiments, each line corresponds to a vessel.

Lambert does not only detail his experiments and carefully enter all conditions and measurements in his table of data, but adds another means of representation of data to it. Lambert visualizes his data, a strategy quite unusual in its time but of which Lambert is a forerunner.<sup>23</sup> As Lambert notes, “I will not make long comparisons with the numbers in this table, because one can see it *d'un seul coup d'oeuil* when the numbers change into figures.” (Lambert 1769, 76) Representing the data in five separate graphs (corresponding to the five different vessels) with the height of the water on the Y-axis, the passing of time on the X-axis, it becomes immediately clear that the all five graphs are more or less parallel to each other, and thus, that the relationship between water height and time is a simple linear one (Figure 1).

Lambert's use of visual strategies is connected to his views on the ‘appearance’ (“Schein”) of things, as explained in his *Phänomenologie*. Perspective or spheric geometry used in astronomy are examples of a ‘language of appearances’ (“Sprache des Scheins”) that can be helpful to simplify certain problems as long as it can be retranslated into the language of reality (Phän. §5). Although visualizations belong to the ‘language of appearances’, they can be useful to determine the truth. In a discussion on figure and symbol (“Figur” and “Zeichen”) in the *Semiotik* (§52–64), Lambert explains that the figure can represent a specific case, a concrete thing, whereas its translation into algebraic signs makes it more general, abstracts from particulars (§57–8 and 62).<sup>24</sup> Translation into algebraic signs makes it possible not only to find one solution, one particularization, but to find – by syntactically linking up the signs – all solutions, all cases (§63–66). However, when doing experimental physics, Lambert details the relationship between *Figur* and *Zeichen*. He does this in the fourth part of the *Anlage zur Architectonic*, the 30th chapter, “Die Schranken”, the limits. Here, he discusses the limits of precision within algebra (rounding off errors e.g.) and within the measuring and recording of phenomena. The precision of measuring instruments, the number of observations etc. all introduce limits to the precision of the obtained results. Therefore, in many cases, a (mechanical or geometrical) construction or a figure may be as precise or as suitable as a calculation for obtaining results, as long as the precision of the data is less than the precision of the construction or figure (Arch. §864-865).

Hygrometry being a young science with but few undebatable results and even fewer standards, visualizations can be of great value. For instance, Lambert sets up some experiments to determine the relationship between air, water, heat and evaporation and

concludes, on the basis of graphs of the experimental results, that air causes the evaporation and that heat (forcing the particles to dilate) contributes greatly to the celerity of the evaporation. On the basis of first figure (here in the upper one in Figure 2) it jumps to the eye that heat and evaporation are correlated, on the basis of a mechanical differentiation Lambert obtains the lower figure in Figure 2. He remarks

It would be quite difficult to give a priori an algebraic equation that satisfies the curve of the fifth figure. [...] but we can always indicate the general symptoms that the curve has to satisfy. (Lambert 1769, 87)<sup>25</sup>

The curve, containing points with a temperature and a water height component, indicates that the celerity of evaporation depends exponentially on the increase of heat. Lambert also notes that the curve implies that evaporation also happens, though slowly, beyond freezing point, and becomes very fast beyond boiling point, though for neither phenomenon does he venture to decide if these are asymptotic axes of the curve. In other words, Lambert is doubtful whether there is an absolute point of temperature where the evaporation begins or stops.

For practical reasons Lambert determines a parable-like curve that locally fits the curve of Fig. V between zero and 60 degrees (Réaumur, corresponds to 0 to 75 degrees Celsius). He simply fits the equation to all experimental points of the curve according to the method set out in (Arch. §894 and 899). The equation is:

$$y = \frac{2}{10}x + \frac{1}{200}x^2 + \frac{13}{72000}x^3 + \dots$$

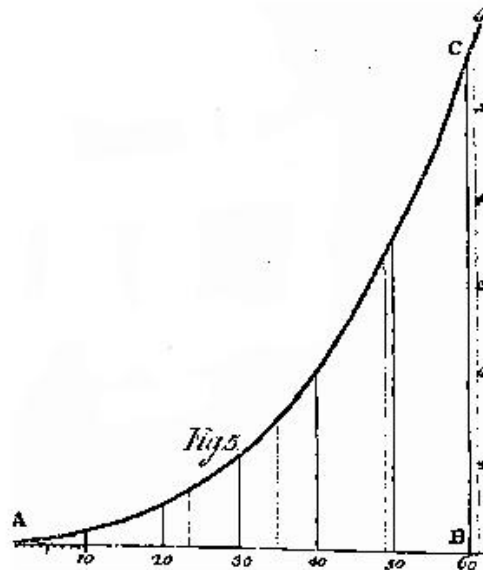
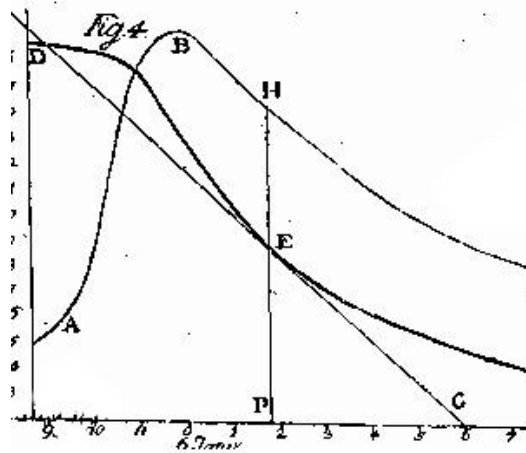
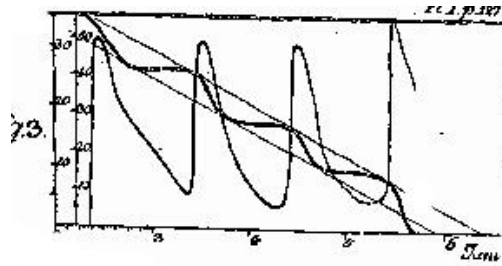
Lambert is perhaps the major forerunner of modern statistical techniques, both graphically and computationally<sup>26</sup>, it need thus not wonder if he experiments a little with this equation. Getting rid of the zeros in the fractional part, Lambert arrives at the equation

$$\frac{4}{3}x + \frac{1}{3}x^2 + \frac{13}{72}x^3 + \dots$$

and remarks that this comes close to

$$x + \frac{1}{2}x^2 + \frac{1}{6}x^3 + \dots$$

which is the power expansion of  $e^x - 1$ . Ultimately he derives a hypothetical differential equation  $dy = mydz$  that governs the growth of evaporation (Lambert 1769, 90), though only for the 'regular' interval given above. Also, the air pressure and the humidity of the air are not taken into account.<sup>27</sup>



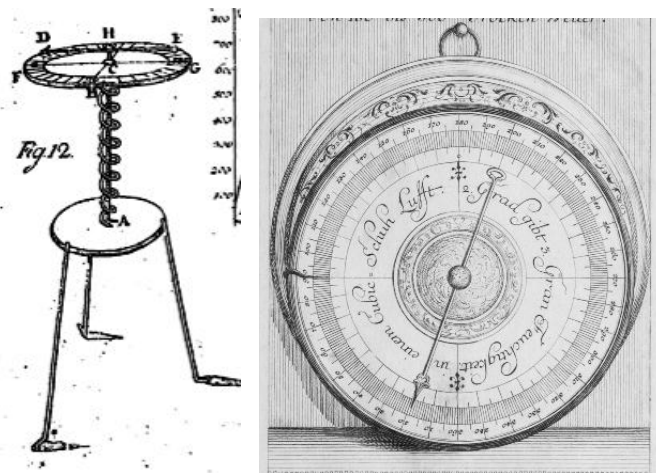
**Figure 2:** Transformation of Graphs in Lambert's Hygrometric Studies: The upper figure represents the temperature (the oscillating curve) and the loss of humidity (the steadily decreasing curve), their correlation is made evident by the intelligent design of the graph showing the meeting points of both curves; the middle figure is a blown-up detail of the upper figure with a tangent on the humidity curve; the lower figure is obtained by graphically displaying the intersection points of the tangents on the humidity curve with the X-axis, i.e. the mechanical differentiation of the humidity curve which generates a curve of the rate of evaporation.

## Setting up the Hygrometer

Asking questions to Nature is much like an experiment in trying to understand and speak its language.

Barometers spoke an intelligible language from the day they were invented; the thermometer did not speak so clearly at first. Only in 1714 did Fahrenheit give to Wolff two corresponding thermometers, and even today this language is only a comparative one. [...] We have to take a closer look at the hygrometers to try and understand their languages and to make it intelligible. (Lambert 1769, 68)<sup>28</sup>

One thus has to find a language to understand the hygrometer, but one also has to render it “corresponding”, communicative with other hygrometers to obtain a homogenous set of data. The language of the hygrometer should ultimately become a quantitative one, either absolute or comparative. Lambert’s previous analysis of humidity and evaporation makes it possible to start designing a hygrometer that speaks of comparative language (within the limits indicated).

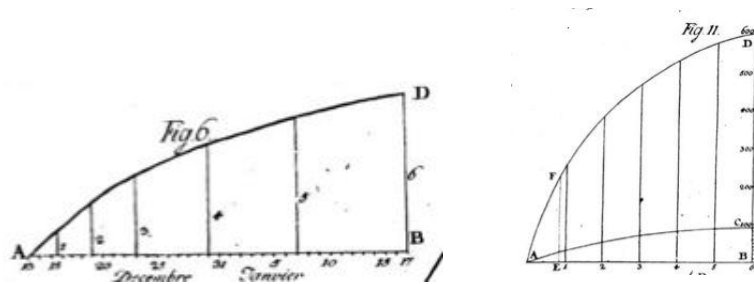


**Figure 3:** Left, Lambert's original set-up of the hygrometer; right, the ulterior design of the Lambert-Brander hygrometer

In the perfection of the hygrometer, the first problem to settle is what substance should be used to measure humidity? Lambert lists the then viable options: Wood, cords, sponges – and chooses the thin cords, with which he had already 15 years of experience (Lambert, 1769, 92). Figure 3 shows his set-up of the hygrometer, a cord wound around a metal stick, with a ‘dial’ on top of it to measure the rotation of the threads in the cords. Given this, “I still had to submit my hygrometers to other tests so as to get to know their language and the law of their variations” (Lambert 1769, 101)<sup>29</sup> This comes down to ‘synchronizing’ the behaviour of the hygrometers with the extremes of the curve of evaporation, to find their points of absolute dryness and wetness.

Enclosing the hygrometers in a bottle and turning the heat on, Lambert finds that from a certain temperature onwards the drying up slows considerably down. Repeating this experience over several days, the hygrometer comes to a stand, displaying his data in a graph, Lambert concludes: “it seems there is something asymptotical there” (Lambert, 1769, 107). Similarly, Lambert tries different procedures to find the maximum of humidity for his hygrometer, and finally comes up with a graph of data where a certain “concavity” in the graph shows up (Lambert 1769, 119–120). As a final check on his experiments in fine-tuning the hygrometer, to compare the rate of evaporation directly with the movement

of the hygrometer's dial, Lambert puts both their parallel evolutions in graphs (Figure 4). The general symptoms of both curves indeed concord, but it is clear that the hygrometer only absorbs and hence displays a percentage of the humidity of the air.<sup>30</sup>



**Figure 4:** The graphs that show the match between the curve of evaporation (left) and the curve of the hygrometer (right)

### Correspondences

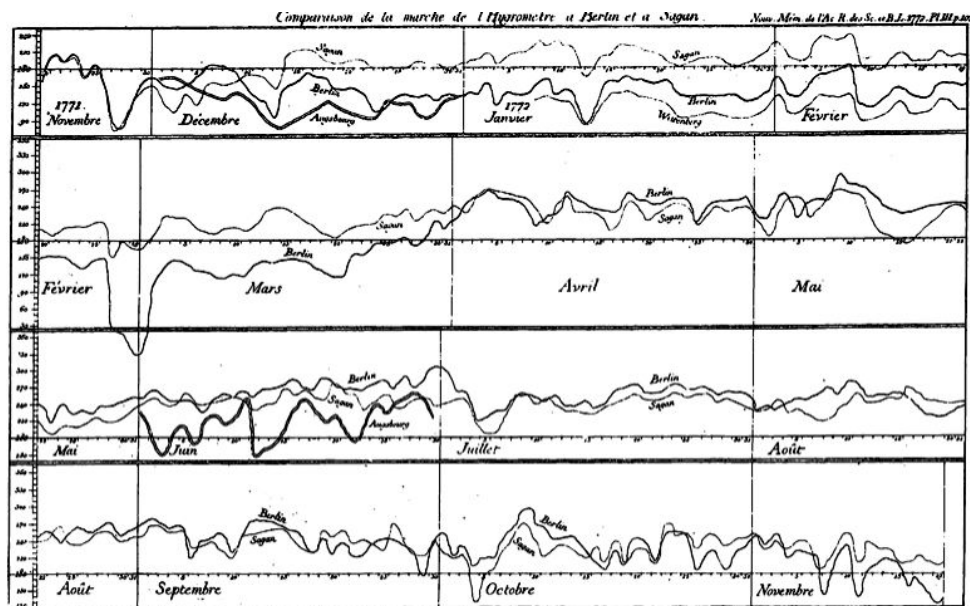
It had been Lambert's ambition in his 1769-article, not only to perfect the hygrometer, to find its quantitative language, but also to find an absolute quantitative language, absolute measurement. His experiments had, however, shown the difficulty (if not impossibility with the instruments of his time) to determine an absolute degree of dryness or wetness. Instead of this, Lambert had been able to define a comparative language with two marker points. These marker points (a 'gentle' minimum and maximum of humidity) were defined by their procedures. Lambert had indicated the dimensions of the tubes used, the quantity of water, heat involved etc. to assure that (Lambert 1769, 107 and 119). This way, assuming hygrometers of the same materials and quality, hygrometers could be made "corresponding" between observers and experiments.

Immediately after the publication of the first paper on hygrometry, Lambert sent a copy of the paper to his long-time friend, the instrument maker Georg Friedrich Brander in Augsburg.<sup>31</sup> In the accompanying letter of November 1771, Lambert instigates Brander to start manufacturing corresponding hygrometers (Lambert 1781-1787, IV, 308). "I would like to see this hygrometer become a common instrument, and then the essay itself can be translated."<sup>32</sup> A dialogue between Lambert and Brander running over more than three years ensues over how to make the hygrometers corresponding.

It becomes rather quickly clear that Lambert's procedures in his 1769-essay to fix the marker points do not function very well. Although the degree of average humidity ("Grad der mittleren Feuchtigkeit") functions rather well as a point of correspondence between two hygrometers, the extremes do not. Other procedures to fix the extreme marker points are discussed and Brander comes with the idea to use the average degree as a fix point together with a scale to 'synchronize' hygrometers per degree.<sup>33</sup> In the end, the two correspondents agree to make a standard hygrometer ("Normalhygrometer") to 'synchronize' the hygrometers (Lambert 1781-1787, IV, 351-352 and 357-358). A tentative correspondence between Lambert's and Brander's hygrometers is finally achieved end of December 1772.<sup>34</sup>

By this time, Lambert had not only his own hygrometric observations, but also those of the prelate Felbiger in Sagan<sup>35</sup>, those of Maschenbäuer's, a friend of Brander in Augsburg, and finally those of Professor Titius in Wittenberg, who had, independently of Lambert, started to make a hygrometer. According to the *Monatsbuch*, Lambert's scientific diary, Lambert devoted April to June of 1772 to comparing and collating the observations (31

Bopp 1916). Finally, everything is put into one large graph, displaying the observations of each participant. The correspondence with Brander and the graph (Figure 5) are the immediate materials that went in Lambert's 1772-article, 'Suite de l'essai d'hygrometrie' (Lambert 1772).



**Figure 5:** Lambert's master graph, collating all hygrometer observations and the basis of his (a priori) derivation of a meteorological law

The graph shows that the observations of all participants are in accordance, at least if one only looks at the extreme points. Although Lambert admits that the material is scarcely enough to find annual regularities or other periodicities, he endeavors to search for an equation fitting the observations. He starts with a hypothetical formula, relating humidity to the longitude of the sun (i.e., to the expected temperature of the season):

$$y=A+B \sin \theta +C \cos \theta +D \sin 2\theta +E \cos 2\theta \dots$$

In a first approximation, the formula becomes  $y=B \sin \theta$ , which fits the curve reasonably well, abstracting from the actual shape of the observations curve, and looking only at the cutting points with a middle axis of intermediate humidity, which is the arithmetical middle of the observations (Lambert 1772, 75–76).

To check his tentative formula, Lambert compares it with the measurements (on a sponge hygrometer) that Crucquius published in the *Transactions of the Royal Society* from 1721 to 1723. Lambert sees his hypothesis confirmed: the increase and decrease of humidity varies more or less like the increase and decrease of temperature, with a phase shift of 4 to 5 weeks (Lambert 1772, 76–79). At long last, Lambert is able to execute part of his program on meteorology, to find periodicities and quantify them.

## Conclusion

The 'exact experimental physics' (Feldman) of Lambert provides an important bridge between an (over)enthusiastic Newtonianism of e.g. Muschenbroek and the standardization of experimental life in the surrounding of the Ecole Polytechnique at the beginning of the

19th century. Lambert's experimentalism is marked by a profound conceptual awareness and a highly practical orientation. Instead of the "literary technology" (S. Shapin) current at the early Royal Society, Lambert analyzes the words used and makes them amenable to quantification and/or mathematization. If the state of the discipline does not allow for a definite or speculative mathematization (as is the case for meteorology), Lambert introduces graphs that display the observational data. These graphs and their interpretation and manipulations function as a sort of midwifery for mathematical formulae that would connect the observational data.

Since the publication of Ian Hacking's *Representing and Intervening*, some have tried to develop a taxonomy of stages, steps and parts within the interplay of theory and practice.<sup>36</sup> It might be argued that the framework Lambert developed in 1764-1765 offers a fine-grained, workable "algorithm" of doing experiments with theory (and vice versa) that precedes these science-theoretical efforts by two hundred years.

On two points, modern theoreticians of science may even learn from Lambert. First, Lambert has a detailed and powerful semiotic theory and the problem of concept formation is amply dealt with. Instead of finding and defining a concept on the basis of experiments or on the basis of theory after experiments, Lambert conducts his concept finding before any experiment or theory, using the resources present in everyday language. This way, understandability between scientists and non-scientists (or for that reason, between different branches of science) is guaranteed, and, perfectibility of the concept is inherent to the definition of the concept, it can be adapted to the outcomes of the experiments and theory. Lambert's semiotic strategies are interesting because they offer a way out of logomachia and out of incommensurable realms of science. The common ground in everyday language and the use of common everyday devices present in language (determination through adjectives and adverbs) are the guarantees for that.

Second, Lambert's theory of science as developed in the *Neues Organon* and the *Anlage zur Architectonic* is open-ended, modular, and especially strong at heuristics. Because Lambert is highly aware of the complexity of many natural phenomena and aware of the limitations of the methods of his time, his philosophical works abound in tips and tricks, in heuristics. His seminal use of graphics in doing science is the most remarkable strategem in his toolkit, Lambert's focus on the study of periodical elements in natural phenomena is another example. Both strategies prepare the ground for the mathematization of humidity and herald new methods (statistical, structural) in mathematics and physics.

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1Original: “Nach diesen vier Fragen entstehen auch vier Wissenschaften, deren sich der menschliche Verstand als eben so vieler *Mittel* und *Werkzeuge* bedienen muß, wenn er mit Bewußtsein das Wahre als wahr erkennen, vortragen und von Irrtum und Schein unterscheiden will.” The four sciences in question (also the four parts of Lambert’s *Neues Organon*) are: Dianoiologie, the laws of thinking; Alethiologie, the difference between truth and error; Semiotik, the doctrine of language and signs; Phänomenologie, the doctrine of appearance.

2In the following we will write references with Dian., Aleth., Sem., Phän. for the four parts of the *Neues Organon*, and Arch. for the *Anlage zur Architectonic* with the corresponding paragraph number. E.g., Sem. §69 refers to paragraph 69 of the 3rd part, Semiotik, of the *Organon*. This accords with Lambert’s own use of referring to these works and helps modern readers to find the correct passage in the different editions that exist of Lambert’s *Organon*.

3Murhard (1798–1799, II, 727–928) gives an overview, with long quotes, of all publications concerning hygrometry. Cfr. also (Feldman 1990, note 36).

4On the place of Lambert’s hygrometric investigations in the history of meteorology: For a contemporary account, see (Murhard 1798–1799, 776–813 ); for a modern account (Feldman 1983, Chapter 4).

5Original: “1. [Ich zeichne] in kurzen Sätzen alles auf, was mir über die Sache einfällt, und zwar so, und in eben der Ordnung, wie es mir einfällt, es mag nun für sich klar oder nur vermuthlich, oder zweifelhaft oder gar zum Theil widersprechend seyn.

2. Dieses setze ich fort bis ich überhaupt merken kann, es werde sich nun etwas daraus machen lassen.

3. Sodann sehe ich, ob sich die einander etwa zum Theil widersprechende Sätze durch nähere Bestimmung und Einschränkung vereinigen lassen, oder ob es noch dahin gestellt bleibt, was davon beybehalten werden muß.

4. Sehe ich ob diese Sammlung von Sätzen zu einem oder mehreren Ganzen gehören.

5. Vergleiche ich sie, um zu sehen welche von einander abhängen und welche von den andern voraus gesetzt werden und dadurch fange ich an sie zu numerotiren.

6. Sehe ich sodann ob die ersten für sich offenbar sind oder was noch zu ihrer Bestimmung erfordert wird,

und eben so 7. was noch erfordert wird, um die übrigen damit in Zusammenhang zu bringen.

8. Ueberdenke ich sodann das Ganze, theils um zu sehen, ob noch Lücken darinn sind oder Stücke mangeln,

theils auch besonders um 9. die Absichten aufzufinden, wohin das ganze System dienen kann,

und 10. zu bestimmen ob noch mehr dazu erfordert wird.

11. Mit dem Vortrag dieser Absichten mach ich sodann gemeiniglich den Anfang, weil dadurch die Seite beleuchtet wird, von ich die Sache betrachte.

12. Sodann zeige ich, wie ich zu den Begriffen gelange, die zum Grunde liegen, und warum ich sie weder weiter noch enger nehme.

Besonders suche ich dabey 13. das Vieldeutige in den Worten und Redensarten aufzudecken, und beyde, wenn sie in der Sprache vieldeutig sind, vieldeutig zu lassen; das will sagen, ich gebrauche sie nicht als *Subjecte*, sondern höchstens nur als *Prädicate*, weil die Bedeutung des Prädicats sich nach der Bedeutung des Subjects bestimmt.” (Lambert to Kant, February 3 1766)

6Original: “Die Routine ist ebenfalls verschieden. *Wolf* abstrahirte gern. *Baumgarten* suchte die abstracten Begriffe auf die Arten anzuwenden, um neue Arten zu finden. [...] *Meier* gebraucht seine Topic. *Euler* calculirt. Dan. *Bernouilli* nimmt gern sinnliche Bilder zu Hülfe. *Muschenbroeck* experimentirt ohne Theorie. Andere nehmen gern Hypothesen an. Jeder hat einen besondern Favoritleitfaden.”

7Philosophical interpretations of this part of Lambert’s work, neglecting its applications and

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mathematical content, can be found in (Berka 1973 and Basso 1999, 170–172).

8Original: “Ces expériences faites à dessein, & dans des circonstances choisies, sont autant de problèmes que nous proposons à la Nature. [...] Elle répond précisément, non à ce que nous croyons demander, mais à ce que nous demandons en effet. A moins donc que d’être érudés & trompés dans notre attente, il faut s’assurer rigoureusement des conditions que le problème présuppose, afin de choisir les circonstances, & d’y adapter l’expérience qu’on veut faire.”

9Original: “La Physique expérimentale se rend absolument nécessaire par tout où il n’y a pas moyen de voir le mécanisme par lequel la Nature opère [...] on y joint le calcul, on y applique les principes de la Mécanique, là où ce mécanisme se développe assez pour être vu, ou qu’il est assez simple pour être conçu.”

10Original: “Le calcul y fournit la précision & l’universalité. L’expérience vérifie l’une & l’autre, & découvre chaque circonstance omise, ou fausement admise. En négligeant le calcul, & la théorie qui lui sert de base, on fait les expériences sans choix & sans dessein. En négligeant les expériences, on court risque de donner dans la chimère, & de produire des calculs applicables à toute autre Monde, qu’à celui où nous sommes.”

11Original: “Wenn eine nach Regeln gemachte Sache gegeben ist, die Regeln zu finden, nach denen sie gemacht worden, oder hätte können gemacht werden.” Quoted after: (Hindenburg 1798, 81).

12For another application of the same concepts, consult (Lambert 1770/1772).

13Original: “Il semble que pour rendre la Météorologie plus scientifique qu’elle ne l’est, il faudroit imiter les Astronomes, qui, sans s’arrêter d’abord à toutes les minuties, commencent par établir des lois générales & les mouvemens moyens. [...] Que n’en est-il de même de la Météorologie? Il est très sûr qu’elle a des lois générales, & qu’il y entre un grand nombre de phénomènes périodiques. Mais à peine peut-on encore deviner ces derniers. C’est peu de chose que les observations qu’on a faites jusqu’à présent, entre lesquelles il n’y a point de liaison.”

14Lambert here pursues and extends an idea of Musschenbroek (Geurts and van Bigelen 1983, 31–52).

15Compare with (Bullynck 2009) and (Goldstein and Schappacher 2007).

16Original: “Il n’est pas nécessaire d’expliquer ce que c’est que l’humidité. On n’a qu’à passer par un brouillard pour s’en appercevoir; car c’est une humidité qui tombe sous la vue & le tact. On la voit encore dans les vapeurs qui s’élèvent des fluides bouillonnans. Elle se rend aussi visible, quand pendant l’hiver elle s’arrache aux fenêtres, ou qu’elle couvre les objets exposés à l’air en forme de brume, ou enfin lorsqu’elle se présente en forme de rosée, qui couvre la surface chevelue des plantes d’une infinité de petites gouttes. Enfin elle s’attache visiblement aux corps vitrés, métalliques &c. lorsque pendant l’hiver on les transporte du froid dans des chambres chauffées. En tout cela il n’y rien qui ne soit connu de tout le monde.”

17For an analysis of Lambert’s views on language in modern linguistic terms, see (Ungeheuer 1990).

18Original: “Diese [Begriffe und Merkmale] werden nun nicht bloß zusammengesetzt oder nur aufgehäuft, sondern damit gleichsam multiplicirt, weil das, was der abstracte Begriff vorstellte, noch neue Eigenschaften bekommt.”

19This was an important issue for Lambert: “The amount of artificial words, especially in cases where the thing at issue cannot be readily presented, becomes a burden for the memory and not all like to learn them and keep them in mind without changing their meanings.” (Arch., §24) (Original: “Denn die Menge der Kunstwörter, zumal wo man die Sache nicht vorlegen kann, wird dem Gedächtnisse zur Last, und nicht jeder bequemt sich gern, sie alle zu lernen, und mit unveränderter Bedeutung im Sinne zu behalten.”)

20Original: “Le degré d’humidité de l’air c’est la masse ou encore le poids de toutes les particules aqueuses, qui nagent dans un certain volume p.ex. dans un pied cube d’air. Voilà donc à quoi doit se réduire le langage des hygromètres.”

21The phrase “anatomy of a concept” is often used by Lambert. The phrase points to ideas developed by John Locke in his *An Essay concerning human understanding* (1690), a book that was together with Wolff’s writings one of Lambert’s most important philosophical sources.

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22Original: “Tâchons donc de la [la humidité] poursuivre dans les principaux phénomènes qu’elle offre pour être évalués & mesurés. Commençons pour cet effet à la voir dans sa naissance.”

23 For a history of visualization in science and Lambert’s prominent early role in it, see (Tilling 1975 and Beniger and Robyn 1978). More on Lambert’s graphical curve-fitting can be found in (Gray and Tilling 1978, 23–26). Laura Tilling analyzes part of Lambert’s work, the theoretical work and the application in magnetism and pyrometry in the unpublished (Tilling 1973, Ch. III, IV), Zeno Swijtink also announced a book project on Lambert’s graphs and methods that never materialized. Lambert’s own theoretical treatment is in (Lambert 1765). The most extended discussion of curve fitting (the one applied here) is, however, found in the *Anlage zur Architectonic*, the 23rd chapter entitled ‘Vorstellung der Größen durch Figuren’ (Arch. §885–902). See (Bullyncck 2008) for a detailed discussion with examples.

24This important philosophical distinction between apprehension through figures and through signs goes back at least to Leibniz who introduced it in his “Meditationes de cognitione, veritate et ideis” (1684). For Leibniz, however, the *cognitio intuitiva* (cognition mediated often, though not exclusively through figures, or at least cognition seen and understood ‘at a glance’) was superior to *cognitio symbolica* (cognition through signs) as a mode of apprehension. Christian Wolff extended considerably on Leibniz’s text, and devoted a large part of his *Psychologia Empirica* (1738) to this issue. Contrary to Leibniz, Wolff insisted on the fact that both modes of knowledge are on the same epistemological level, and that especially the symbolic cognition is of the foremost importance in science (algebra being the prime example).

25Original: “Il seroit assez difficile d’assigner a priori une équation algébrique, qui satisfait à la courbe qu’offre la cinquieme Figure. [...] mais nous pourrons toujours indiquer les symptomes généraux, auxquels cette courbe doit satisfaire.”

26For Lambert’s graphics see footnot 24, for Lambert’s computational methods see (Sheynin 1970/1971a and 1970/1971b) and (Bullyncck 2008).

27Lambert’s equation corresponds more or less to the modern simplified equation  $dy/dx = -ky$  for the rate of evaporation. A more elaborate equation, taking into account all circumstances (air pressure, sporadic elements in the water ...) has been given by (Penman 1948).

28Original: “Les baromètres, dès sa première invention, parla au moins un langage intelligible; le thermomètre ne le parla pas d’abord. Ce n’est qu’en 1714 que Fahrenheit remit à Mr. Wolf deux thermomètres correspondants, & encore aujourd’hui ce langage n’est que comparatif. [...] [on doit] considérer [les hygromètres] de plus près, pour apprendre à en connaître le langage, & à le rendre intelligible.”

29Original: “Il restoit encore à soumettre mes hygrometres à d’autres examens, qui devoient aboutir à en faire connaître le langage & les loix de leurs variations.”

30To explain how the air contains a high percentage of water, Lambert refers to his work on the speed of sound in humid air, (Lambert 1768).

31More on Brander in (Brachner 1983, 15–28 ). The hygrometers constructed by Brander can be found in the same volume p. 258 and 260. Lambert had been in correspondence with Brander since 1765 and pursued it until his death in 1777. The correspondence was posthumously edited by Johann III Bernoulli as the fourth volume of *Lambert’s deutscher gelehrter Briefwechsel*.

32Original: “Ich wünschte diese Hygrometer gemein zu machen, und dann könnte die Abhandlung übersetzt werden.” (Lambert 1781-1787, IV, 307)

33Brander to Lambert (April 20, 1772): “wenn gleich die mehresten [Hygrometer] bey mittlerer Feuchtigkeit ziemlich genau harmoniren, so differiren sie doch öfters untereinander sehr in beyden Extremis der Trockenheit und Feuchtigkeit. Daher ich auf den Gedanken verfallen bin; man sollte sie nach einem einmal angenommenen Etalon durch alle Grad abgleichen und jene in diese reduciren; dadurch erhielte man durchgehends einerley Valor und würde auch manches tüchtiges Stück Saiten können beybehalten werden.” (Lambert 1781-1787, V, 324)

34Still, two years later, small variations often occurred. Lambert complained about the sometimes

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failing correspondence in his correspondence (Lambert 1781-1787, IV, 409 ).  
35Sagan lies between Frankfurt/Oder and Görlitz.  
36See (Hentschel 2000) for an overview.

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