Johann von Lamont and his magnetotelluric experiment in 1862

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SUMMARY

Earth currents were first observed in the middle of the 19th century, closely related to magnetic field variations. Particularly the magnetic storms of 1859, which belong to the strongest ones ever experienced, destroying telegraphic constructions in the USA, Europe and Australia, made Johann von Lamont start with experiments about the nature and origin of earth currents. Among these experiments he presented for the first time a method to calculate the thickness of a high conductivity layer in southern Germany.

Keywords: earth-electric current, magnetic storms, Lamont

INTRODUCTION

The geophysical sounding method "magnetotellurics" was formulated and published by Louis Cagniard in 1953, in particular in Western Europe. Later on it became known that even before in 1950 A.N. Tikhonov published an equivalent theory in Eastern Europe, in Russian. Both were henceforth appreciated as the discoverers of magnetotellurics. However, a few years ago we could read that a Japanese author, M.H.Hiramaya, published an equivalent theory already in 1934.

Quite recently the question came up somewhere in the MT community whether Johann von Lamont could have been the very first who "invented" the magnetotelluric method. He actually published in 1862 a book about earth currents. There he describes an experiment to measure electrical currents in the earth and the corresponding magnetic field. He then uses the ratio of the amplitudes to calculate the depth range of the sediments beneath his geomagnetic observatory close to the capital of Bavaria, now known as Fürstenfeldbruck (FUR). It appears thus clearly as a magnetotelluric experiment and Lamont as a pioneer of that geophysical method.

This remarkable historical event fell completely in oblivion till K.-P.Sengpiel mentionend this experiment and the surprising result in his dissertation at the University in Munich in 1968, however without discussing any detail of that work. In 1991 a special issue of the "Münchener Geophysikalische Abhandlungen (Munich Geophysical Treatises)" in honour of the 150th birthday of the observatory a number of contributions appeared, also to honour the founder of this geomagnetic observatory, Johann von Lamont in 1840. One of the contributions was written by Gustav Angenheister, the former director of the institute and observatory, about those experiments to discover the unknown nature of earth currents.

Johann von Lamont was at his lifetime a well-known and appreciated scientist. His name and his merits in experimental discovery of the magnetic field of the Earth are well known up to the present. He was member in almost all scientific academies in Europe; he was professor at the Munich University, director of the astronomical and geomagnetic observatory. And he was ennobled by the Bavarian King Ludwig the 2nd. Mares on the planet Mars and on our Moon bear his name.

Lamont's scientific interests were very broad, in particular in astronomy. Among them, for a few years, the study of the origin of electrical currents in the Earth which received global attention with a magnetic storm on 1st September 1859 which destroyed telegraphic constructions worldwide. Already in October of that year he installed several experiments in his observatory and started observations one month later. In 1862 he published the experiments already in a book (Lamont, 1862).

This book is actually a comprehensive final report on a research project of only 2 years with the aim to identify the nature of the Earth currents. On pages 32-38 Lamont describes an experiment to measure electrical currents at the Earth's surface and develops a mathematical algorithm to calculate their depth range which we now interpret as the depth range of well conducting sediments.

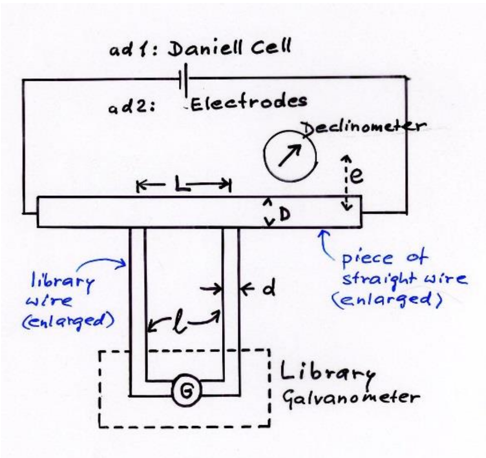
In this contribution I will try to reformulate the mathematical and physical deduction of Lamont, both in the original as well as in modern terminologies. Reading and understanding texts from earlier centuries, written in their national languages, the wording and the style, of that time, is a difficult piece of work, possibly subjected to ambiguous interpretations.

Additionally, the formulation of physics relations in a rather archaic state of knowledge as here of EM, in particular before James Clark Maxwell cannot be translated in modern terms at all.

The knowledge and understanding of the origin and effects of electrical currents were still at its very beginning in that time not much more than 60 years after Luigi Galvani and Alessandro Volta in Italy discovered the first electrical phenomena on frogs. Still at the time of Lamont electrical currents were due to electrochemical (galvanic) or thermoelectrical origin, induction currents just started their career. The idea of Lamont was that earth currents are either one these three types or a completely new type of electrical current. This was the aim of this research project where the following “magnetotelluric” experiment only plays a minor role.

THE EXPERIMENT

The construction and the properties of the instruments for measuring the magnetic fields and the electric currents occupy a large part of the book. Lamont was a very gifted maker of instruments. It is startling, however, that none of these instruments were calibrated in any unit other than the number of scale divisions of the deflection of the needles: the most basic unit.



Following Lamont, we will use the original terminology g for current intensity, instead of the modern expression current density j. Lamont measures the earth current intensity with two buried iron plates (0.98x0.79 m²) about 100 m apart, connected by a copper wire. The current is the product of current intensity and cross section of the wire, resistance the product of a resistivity (which never appears since it will always cancel out) and length divided by the cross section of the wire. The electric current flows from the electrode plates through the wire and the galvanometer, its strength is designated as N, i.e.:

$$N = g\,B\,H \qquad (1)$$

with N the number of divisions taken from the galvanometer, B = breadth (width) and H = height of the electrode-plates.

Lamont's primary aim was to determine the depth of origin of the currents. He introduced a simple model of a plate with thickness k on top of the region in which this current was flowing. To solve the problem mathematically, he applied the method of Biot-Savart.

The result was

$$Y' = 2\pi g\,k \qquad (2)$$

The equation looks familiar as it resembles the gravity formula for the corresponding Bouguer-plate, with g as mass density and k as thickness of the plate. The factor 2π may be due to a unity system which, however, is never mentioned and does not play a role here because this relation will appear finally only in ratios of different depths k such that this factor cancels out.

The declinometer indicates the according magnetic field Y’ as a deflection of the needle

$$\Delta\delta = \frac{2\pi g k}{X}$$ (3) with X as the restoring force of the magnetic needle.

k could not be calculated since $\Delta\delta$, g and X were unknown. Therefore he set up the experiment in two steps:

> A long straight wire is suspended parallel to the magnetic meridian above the ground and a current of strength I is fed in with a battery. The needle of the declinometer will be deflected by "m" divisions and the galvanometer connected in a by-pass circuit is deflected by " m' " divisions. If the battery is disconnected, the current flow is underground from the electrode plates. While the galvanometer shows no change, the declinometer will now also indicate the magnetic field from the underground layer of depth k according to Equation 2.

The mathematical formulation of both parts of the experiment is:

<u>Ad 1.</u> The magnetic field of a current through the long straight wire, measured at a distance e perpendicular to it, is:

$$\delta Y = \frac{1}{2}\frac{D^2\pi}{e} g \; \{= \frac{2I}{e}\} \qquad (4)$$

D is the cross section of the long wire. The term in curly brackets {} is added to show Biot-Savart's law in the modern customary expression for comparison.

δY is acting perpendicular to X, the horizontal magnetic field strength, which serves as the restoring force on the magnetic needle

$$m = \frac{D^2\pi g}{2e\,X} \; \{= \frac{2I}{eX}\} \qquad (5)$$

To determine the current through the galvanometer Lamont attached the galvanometer with two clips c and d (terminals) somewhere towards the middle of the long straight wire. The length of the shorter of both pieces c-d is L with cross section D, the longer piece of the wire (indeed reaching until the library of the observatory where the galvanometer was installed) is l with the cross-section d.

The resistance of the short piece is thus:

$$R_{short} = \frac{L}{(D/2)^2\pi} \qquad (6)$$

The resistivity of the wires will cancel out in the following since the material is always copper.

For the longer "library" segment, we yield:

$$R_{long} = \frac{l}{(d/2)^2\pi}$$ (7) The current through the galvanometer circuit will approximately be equal to the current though the long straight wire multiplied by the ratio of the resistances of the short wire and the long wire. Instead of writing the current strength I, the deflection in number of divisions on the scale is given by (in curly brackets again the modern expression):

$$m' = \{I \frac{R_{short}}{R_{long} + R_{short}} \approx I \frac{R_{short}}{R_{long}}\} = (D/2)^2\pi g \frac{L}{(D/2)^2\pi}\frac{(d/2)^2\pi}{l} = \frac{1}{4} d^2\pi \frac{L}{l} g \qquad (8)$$

Ad 2: According to Equation 2 the deflection of the declinometer needle is:

$$N = \frac{2\pi g H}{X} \qquad (9)$$

for a layer with thickness H (the electrode depth range) and

$$\hat{N} = \frac{2\pi g k}{X} \text{ for a layer with thickness k} \qquad (10)$$

From Equation 5 we take g

$$g = \frac{2mXe}{D^2\pi} \qquad (11)$$ and insert it into Equation 9

$$N = \frac{2\pi H}{X}\,\frac{2mXe}{D^2\pi} = \frac{4mHe}{D^2} \qquad (12)$$

The current flows from the electrode plates through the galvanometer

$$N' = gBH \qquad (13)$$

B and H specify the dimensions of the electrode plates.

The current density g is now expressed by the current density causing the battery driven deflection m' in Equation 8:

$$g = 4m'\frac{l}{L}\,\frac{1}{d^2\pi}$$ and inserted in (13): (14)

$$N' = 4m'\frac{BHl}{\pi d^2 L} \qquad (15)$$

Now Lamont uses these observables as defined in Equations 9, 10 and 15 in pairs of impedance-like (E/H) combinations:

$$p = \frac{N'}{N} = \frac{BHl}{\pi d^2 L}\,\frac{D^2}{4mHe} = \frac{m'BD^2 l}{md^2 Le} \qquad (16)$$

And for the "layer of thickness k":

$$f = \frac{N'}{\hat{N}} = \frac{4m'BHl}{\pi d^2 L}\,\frac{D^2}{4mke} = \frac{m'BD^2 l}{m\pi d^2 Le}\,\frac{H}{k} = p\frac{H}{k} \qquad (17)$$

RESULT

N' and $\hat{N}$ are the observed deflections of the declinometer and the galvanometer in scale-divisions. Lamont reports that he observed on 17th September 1861 exactly the same deflections on both scales, such that f = 1.0. p can then be calculated from the experimental set-up which consist only of length measures in Bavarian Foot bf (1 bf = 0.2920 m),
L = 5.0 bf,
l = 272.7 bf,
H = 3.35 bf,

B = 2.69 bf,
e = 1.9bf ,
m = 8.17,
m' = 83.57,
D^2/d^2 = 5.407 (by weighing of equally long pieces of both types of wire).
Using these values, with Equation 16 yields p = 1360.
The experiment was repeated several times, the final mean value was p = 1483.
The thickness of the electric current layer, and thus of the conductive subsurface layer can be calculated using Equation 17:
k = p H = 4968 bf = 1450 m.
The geomagnetic observatory at that time 1861 was built on the sedimentary Molasse basin. The depth of the sedimentary sequences beneath the observatory as determined by seismological experiments and by drilling 100 years later is close to the value determined by Lamont.

DISCUSSION

Lamont himself mentioned aspects which could influence his results:

Current concentration: From his own experiments he knew that the currents, flowing primarily straight and parallel to each other, will concentrate towards the electrodes. His calculations did not consider this concentration effect and he therefore assumed that this neglect may be a sensitive source of an inaccurate result. The concentration effect should be determined experimentally but was not pursued further.
The current density may differ in all earth layers due to different conductivities. He discussed some solutions which, however, will not be discussed here.

A question not really answered by Lamont was whether the observation of f = 1.0 was mere coincidence or on purpose. In a footmark he remarked that the wire to the galvanometer was extended by a piece of 133.3 bf, up to 272.7 bf. This changed the resistance R_{long} and thus the factor p: It is likely that Lamont adjusted this part of the experimental set-up to yield f = 1.0. This arrangement was at least one of the means of observing accurately two simultaneous and independent variables in one experiment at a time when recording techniques not yet existed.

The derivation of Lamont's Formula by the Thin Sheet approximation of Waits recursion algorithm:

The model of a low resistive layer with the conductivity σ_1 and the thickness d upon the substratum of lower conductivity σ_2 is indeed very convenient for the applied method: Starting with C at the upper surface of the second layer $C_2 = 1/K_2$, it follows

$$C_1 = \frac{1}{K_1} \frac{K_1/K_2 + \tanh(K_1 d)}{1 + K_1/K_2 \tanh(K_1 d)} \approx$$

$$\frac{1}{K_1} \frac{K_1/K_2 + K_1 d}{1 + K_1^2/K_2 d} =$$

$$\frac{1/K_2 + d}{1 + K_1^2/K_2 d} = \frac{\frac{1}{K_2}}{\frac{K_2 + K_1^2 d}{K_2}} = \frac{1}{K_2 + K_1^2 d} \approx$$

$$\frac{1}{K_1^2 d} = \frac{1}{i\omega\mu_0\sigma d}$$

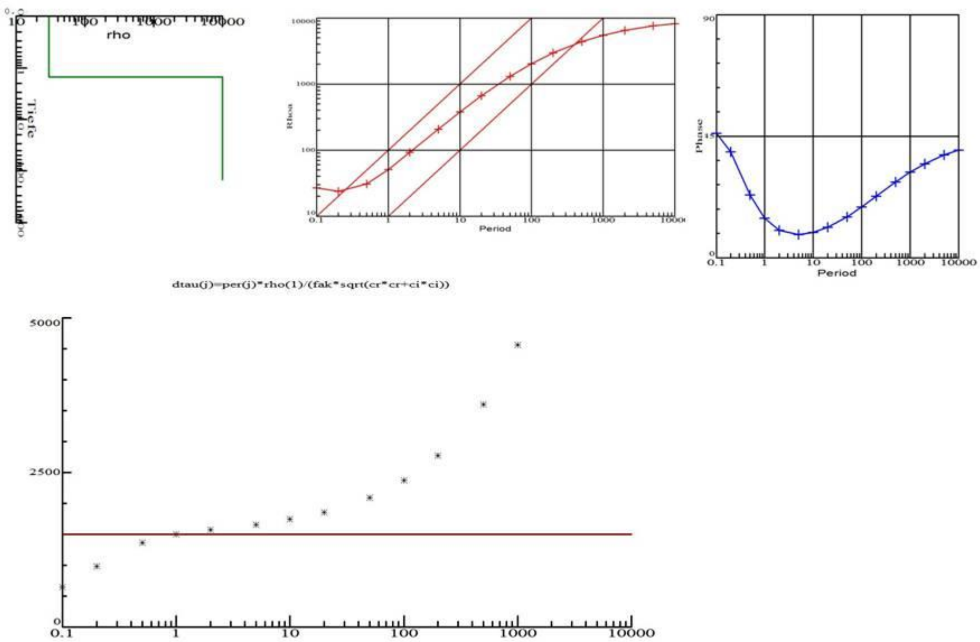
with $K_n = \sqrt{i\omega\sigma_n \mu_0} = \dfrac{1+i}{p_n}$ p = depth of penetration

$$C_1 = \frac{E}{i\omega B} = \frac{E}{i\omega\mu_0 H}, \text{ and } j = \sigma_1 E,$$

we get $\dfrac{E}{H} = i\omega\mu_0 C_1 = \dfrac{1}{\sigma_1 d}$, thus $\dfrac{j}{H} = \dfrac{1}{d}$

This is the relation which Lamont used instead of the traditional E/H relation in magnetotellurics – of course without the knowledge of this derivation.

I will demonstrate these relations with a simple numerical model as in the case discussed here. We consider a layer of 30 Ohm m and 1500 m above a basement of 10000 Ohm m, in a period range 0.1 to 10000 sec. The result shown in Fig.2 displays clearly the thin sheet approximation with the almost 45° rise and the vanishing phase. The calculation of the thickness of that upper layer is in that period range almost independent of the periods. All this shows that Lamont was a fortunate scientist.



G. Angenheister also discussed whether Lamont's result could be seriously considered as a real achievement. He did not take up his detailed derivation of the mathematical and physical formula. Instead he took up the critical though qualitative remarks of Lamont, which in particular considered the intensity of concentration of the current lines towards the electrodes and the calculation of the current density, by taking the total current and the dimensions of the electrode plates into account. He concludes that the result (the 1450 m) is just accidental and could have been any number.

It may be a philosophical problem: there are only 3 quantities: j, H, d. If H and d are correct, why should and can j be wrong? Probably Lamont's and Angenheister's doubts are not justified so firmly. In each case, Angenheister's final remark holds still true: This experiment was probably the first one to investigate the subsurface with electromagnetic methods.

CONCLUSION

Forgotten and vanished names of pioneers of science are not rare; the reasons for it are numerous. One reason may be after a century or even more the style of their quaint writing is hard to understand. This problem came up when the scientific language of communication changed from classical Latin which remained unchanged since the time of Cicero to the different national languages. The classical Latin could be understood over the centuries and everywhere. It is interesting that Galvani has still written his most important work “De Viribus Electricitatis Artificialias in Motu Musculari” 1791 in Latin (W. Stroh 2007). Lamont was writing in German in the style and wording of the mid 19th century. German language has changed over these 150 years, and nobody would describe a simple geoelectric experiment as Lamont has done it. This was indeed the difficulty in reading and understanding the text, which required sometimes a break of days to even weeks and months to understand and then to proceed. The almost forlorn and forgotten pioneers of MT, A.N.Tikhonov and M. Hirayama have written in their national languages, i.e. Russian and Japanese. L. Cagniard however published in English, not in his native language French.

Lamont did not only write in a time dependent national language, but he considered also only a small part of the MT method, i.e. its thin sheet approximation. One could now argue that also Cagniard considered only a small part of the MT method, i.e. the 1D version. But the deciding aspect of Cagniard, Tikhonov and Hirayama was that they constructed a solution on the full induction problem.

If we could ask Lamont himself today whether he would feel as the first man who did magnetotellurics he would probably disagree. He was a strong character and – following his book about earth currents - was amused, sometimes disgusted by colleagues who believed in more than they could measure. It is not unlikely that Lamont would have been sceptical about the equations introduced some years later by James Clerk Maxwell, even though he was native Scotsman like him.

Final remark: Lamont did this experiment to find out about the nature and origin of the earth currents. He discussed the reasons to discard the currents of galvanic type, then the currents of thermoelectric type and to our surprise also the currents of induction type. For this latter type he even performed an experiment, which he described briefly in a footnote. The mistake was that he did not consider the small induction number of the experimental setup which of course was not yet invented before Maxwell’s theory. Therefore he proposed an interesting philosophy on the true nature of the earth currents: Since it was for more than 100 years known that the earth globe is negatively charged (with $5.9\text{x}10^5$, Erich von Kilinski, 1958), there should exist a negatively charged fluidum more or less close to the earth’s surface. The problem left was to find out how to move this electric negative fluidum such that the observed electrical currents appear. He left this problem unsolved.

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