On the Treatise "Electrodynamic Measurements, in Particular on Electric Oscillations"

Wilhelm Weber

Abstract

English translation of Wilhelm Weber's 1863 paper "Ueber die Abhandlung *Elektrodynamische Maassbestimmungen, insbesondere über elektrische Schwingungen*", [Web63] related to [Web64].

1   Introduction by the Translator

Wilhelm Eduard Weber, his Time, his Research, and his German

Dear readers,

in Weber's time (he lived from 1804 till 1891), the conditions for a scientific publication were considerably different from today's: 1st scientists and science journals were scarce then; 2nd the scientists could afford to write in a lengthy and, quite contrary to concise writing, circumstantial style. The 19th century German language in particular lent itself for "mile long" sentences, compilations of interwoven secondary clauses; the German term is *Schachtelsatz*. "Involved period" sounds a bit too innocent, however; German is among the world champions, maybe second only to Latin, when it comes to constructing a jungle of ideas in one go. Such style may have been considered then as "elegant". Scientists adapted their writing to their thinking and they were cautious about the details of their publications. Their extensive way of formulating may also be considered as trademark of honesty. We find other German writers in that tradition, take Einstein or Woldemar Voigt, whose messages are presented in an unusually rich bouquet of words. Reading Weber's original, we meet an exceptionally detailed writer with the knack of complicated formulations, often offering a tedious text to his readers who have to struggle through the syntax. Weber was a meticulous and cautious researcher, sticking to all (often unnecessary) details, thereby repeating quite a few of them that burden the text. Nobody writes like that any more. In my high school days, we were strictly advised not to overload our sentences. The German proverb "In der Kürze liegt die Würze" (brevity is the soul of wit) is an official present day motto — it certainly was not Weber's.

The 19th century nomenclature, too, differs from what we are used today. Some examples: *Elektricität* is best understood as charge (Weber uses *Ladung*, too, but mostly *Elektricität*); *Kette* (chain) is translated by circuit; current intensity (*Intensität*) and current density (*Dichte*) occur interchangeably; we take density; the "encounter of waves" (*Begegnung von Luftwellen in Orgelpfeifen*) is our interference; a "steady, or persistent, current" (*beharrlicher Strom*) is our direct current, DC; Weber's title *Maassbestimmungen* is ambiguous — it hints both at *measurements* and at his aim to establish "*absolute units of measure*" by measurements. We chose "measurements", always keeping in mind also the units of measure so important for Weber.

To give you a taste of Weber, here is a single(!) sentence from his present introduction to the treatise "Electrodynamic Measurements" followed by a "modernized" translation containing the essential information. The version

that tries to stay close to Weber makes part of the whole translation.

> *Die Frage über die Fortpflanzungsgeschwindigkeit elektrischer Bewegungen in Leitungsdrähten lässt sich danach überhaupt nicht so einfach beantworten und noch weniger durch eine Messung, wie sie Wheatstone auszuführen versucht hat, entscheiden, wie daraus ein leuchtet, dass sehr verschiedene Geschwindigkeiten bei diesen Fortpflanzungen zu unterscheiden sind, und dass zumal bei längeren Leitungs drähten, wie der Wheatstone'sche oder die zu Telegraphen gebrauchten, die Fortpflanzungsgeschwindigkeit der grösseren Wellen, welche bei kürzeren Drähten der des Lichts nahe kommt oder sie noch übersteigt, sogar bis auf Null herabsinken kann, und dass darüber hinaus, wo der Ausdruck der Fortpflanzungsgeschwindigkeit imaginär wird, von Fortpflanzung der Bewegung durch Wellen gar nicht mehr im gewöhnlichen Sinne die Rede sein kann, sondern blos von einer asymptotischen Annäherung der Bewegung an ein bestimmtes Gleichgewicht, die als reine Dämpfung oder Absorption betrachtet werden kann, und die bei der Wichtigkeit, die sie für längere Leitungsdrähte, namentlich für Telegraphendrähte, hat, noch nähere Untersuchung verdient.*

> *The question concerning the velocity at which the motion of charges propagates in conductors is, thus, not at all an easy one to answer, let alone one to be decided by a measurement like Wheatstone's effort. Clearly very different propagation velocities have to be distinguished. Above all, in quite long wires as used by Wheatstone or in telegraphy, the velocity of long wavelengths may even drop to zero, while in short wires it may approach or even surpass that of light. Furthermore, when the expression for the velocity becomes imaginary, ordinary wave propagation is out of the question, leaving only the approach to an equilibrium, to be considered as pure damping or absorption. For long wires, especially as in telegraphy, its importance deserves closer investigation.*

Why then are we offering a tentative translation that tries to stay strangely literal at the risk of looking like old fashioned "German-flavored English"? Staying closer to the original may help to understand Weber better in the context of his time and of the spirit of 19th century science. You may have

to read sentences twice, likewise to rework the somewhat complicated and circumstantial mathematical part that seems to fit the linguistic part. Anyway, a tedious study may prove rewarding when it lets the reader pause to reconsider the information contained in Weber's honest and cautious way of presenting science. Enjoy!

<div align="center">Peter Marquardt[1]</div>

2 Weber: On the Treatise "Electrodynamic Measurements, in Particular on Electric Oscillations"

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On the Treatise "Electrodynamic Measurements, in Particular on Electric Oscillations"
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By Wilhelm Weber[2,3,4]

The task to examine more closely the *forces* mutually exerted by electric particles or which are exerted on them by other bodies, which has been the main subject of the preceding treatises on electrodynamic measurements,[5] is closely followed by a second task, namely, to examine carefully the *motions* performed by the electric particles driven by all these forces or to establish the *laws of the motion of electricity* derived from the laws of those forces; for the knowledge of these forces above all is to serve to gain a more exact knowledge of these motions than is possible by direct observation.

This second far-reaching task of electrodynamics has found but little attention yet, and it is justified to ask for the reason why it happened that it has been hardly tried to develop further the foundation given by the knowledge of the forces. Obviously, the reason is that the foundation itself has not yet been considered as completely finished and secured. That is to say, it could be called to doubt whether all forces acting on the electric masses were indeed already known, or whether besides the known electric forces acting

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[2][Web63] related to [Web64].

[3]Translated by P. Marquardt, marquardtp@gmail.com, and edited by A. K. T. Assis, www.ifi.unicamp.br/~assis

[4]The notes by H. Weber, the editor of the fourth volume of Weber's *Werke*, are represented by [Note by HW:], while the Notes by A. K. T. Assis are represented by [Note by AKTA:].

[5][Note by AKTA:] [Web46] and [Web07], [Web52b], [Web52a], [KW57] and [KW19].

at all distances, any yet unknown *electric molecular forces*, limited to immeasurably small regions of influence, co-act which should be investigated before one tried to develop the laws of motion of electric masses depending on them. Even the reliability of the *resistance law of ponderable conductors* could be called to doubt, at least when the same should be applied to the development of laws for *non-uniform* and *rapidly increasing* motions; because this law, first formulated by Ohm,[6] can be considered as safely established only for *steady* currents.

The only effort to solve this task in a somewhat more general way has been reported by Kirchhoff in Poggendorff's Annals 1857, Vol. 100 and 102,[7] but, as declared by Kirchhoff himself, it is restricted to very thin conducting wires and to the assumption of a more general validity of Ohm's law than has been proven, namely, its validity also for non-uniform and rapidly increasing currents. Furthermore, the development of the laws, as far as conducted up to now, does not allow a more detailed test by experience.

In particular, the following two objections against the existing development are in order, namely, *first* that, should the requirements of the fineness of the conducting wire be merely approximately fulfilled, the wire should be much finer than all wires available or producible by existing means; *second*, that, apart from this, the assumption of a more general validity of Ohm's law would not be compatible with such a fineness of the conducting wire; because the finer the wire, the more pronounced become the deviations from Ohm's law for non-uniform and rapidly changing currents.

It has therefore been tried to establish the laws of motion of electricity in *closed* conductors independent of those more or less unrealizable and dubious assumptions and as far as necessary to develop the latter at least for the simplest case when the closed conductor is a *circle* in order to test the theory by means of experience.

The result has been that, after each perturbation of the equilibrium of the electricity in a closed conductor, indeed *propagations* of electric motions take place with determinable *velocities* which could be called *electric waves*; but those *electric waves* are fundamentally different from *air* or *aether waves*, through which sound and light are propagated, which for example is evident from their velocity being dependent on the *length of the path* (the length of the closed conducting wire) they have to pass through which completely contradicts the laws of propagation of other waves. Likewise, the *wavelength* in each wave train to which a certain *velocity of propagation* belongs, is in a

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[6][Note by AKTA:] [Ohm26], [Ohm27] with English translation in [Ohm66].

[7][Note by AKTA:] [Kir57b] and [Kir57c], with English translations in [Kir57a] and [GA94], respectively.

certain ratio to the length of the path: namely, it always represents an *aliquot part* of the total length of the closed conducting wire as is usually assumed for those standing air oscillations that are produced by their interference in organ pipes. But the laws of decomposition of those types of wave trains that are valid in air are not applicable to electricity, because here wave trains with different wavelengths have different *propagation velocities*.

Consequently, the question about the *propagation velocity* of electric motion in conducting wires is not at all an easy one to answer and even less to decide by a measurement, like Wheatstone tried to perform,[8] as is clear from the various velocities that have to be distinguished for these propagation velocities, and that particularly the propagation velocity of the longer waves which may approach that of the light or may even surpass it in shorter wires, may even decrease to zero especially in longer wires like those utilized by Wheatstone or those used for telegraphs; and moreover from the propagation of motion [of electricity] by means of waves in the usual sense which is out of the question when the expression for the propagation velocity becomes imaginary, but is just an asymptotic approach of the motion to a certain equilibrium which can be considered as pure damping or absorption and which deserves closer investigation in view of its importance for longer conducting wires, namely, telegraph wires.

The case when the expression for the propagation velocity for the bigger wave trains becomes imaginary (where for this part of the motion, as already noticed by Thomson and Kirchhoff,[9] similar laws like that for thermal conduction may hold) deserves special attention when another part of the motion always remains which produces smaller wave trains for which the expression for the propagation velocity stays real. Hence there are indeed wave trains with certain propagation velocities in such a wire after each disturbance of equilibrium, however, they do not constitute a pure wave motion but are mixed with motions that are subject to other laws, namely, those analogous to heat conduction.

If one considers all relations that arise from such a mixture of motions which change according to completely different laws, then it becomes self-evident that the *non-simultaneity of sparks* at very distant ruptures of a long conducting wire observed by Wheatstone by no means allows to conclude a definite propagation velocity, that Wheatstone's method of observation, be it as practical as is, is not suited at all for the present purpose, and that one may succeed with difficulty to find other methods to determine the laws

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[8][Note by AKTA:] [Whe34].

[9][Note by AKTA:] [Tho56] and [Kir57b] and [Kir57c], with English translations in [Kir57a] and [GA94], respectively.

of all changes of motion of the electricity in a conductor after a disturbed equilibrium by *pure experimentation*. The purpose of the observation rather seems to be restricted to *test* the laws obtained from otherwise acquired knowledge of electricity, for which purpose it is thus necessary to place this derivation before the laws, all the more as the laws derived and to be tested must themselves serve as *guide* in order to find the methods of observation that are best suited for the test.

Such a test, if it is to be exact, will always demand fine-tuned measurements. If one considers that the finest measurements in physics concern either *equilibrium phenomena*, or *steady motions*, or *periodically occurring motions* (oscillations), it is manifest, apart from constant currents, to establish a test method also for the observation of *periodically regularly occurring motions*, or *oscillations*, of electricity in conductors, taking for granted that there are means for the fine execution of such observations.

Periodically occurring motions of electricity in a conductor, however, cannot arise all by themselves, but always by repeated excitation, and the quick rotation of a small magnet around an axis perpendicular to its magnetic axis offers itself for their *production* as the simplest and, for finer observations and measurements most practicable method, as well as for their *observation* the effects they bring about when the electrodynamometer is switched on. In order to obtain a practicable guide for such observations, however, the laws of such *electric oscillations* have to be developed first.

From this development it follows that, with the magnet in continuous rotation, the electricity in all parts of the closed conductor will be set in regular continuing oscillation which is oppositely equal for positive and negative electricity. The period of an oscillation is equal to the period of half a rotation of the magnet. However it also follows that the *oscillation amplitudes* and the *oscillation phases* of the electricity at different positions of the closed conductor have to coincide perfectly, not only when the electromotive forces simultaneously exerted by the rotating magnet are equal everywhere, but that they should exhibit almost unnoticeable differences even when these forces are quite randomly distributed in the circuit. Thus, in general, the oscillations may be considered completely equal and simultaneous which extremely simplifies the observations of electrical oscillations in closed circuits which, according to the theory, should prove almost correct also in very long circuits.

This remarkable result has been tested *first* by really performing observations of oscillations under conditions that are favorable for the comparison of the *amplitude* at various positions of a long circuit which showed that the deflection of the switched-on dynamometer that is proportional to the square of the oscillation amplitude deviated by less than 1/3 of a scale unit out of

846 scale units as an average from six observations for two positions almost five miles apart; with respect to unavoidable observational uncertainties, this means that there was no difference of the oscillation amplitude.

Second, the oscillations have been observed under conditions favorable for the determination of the *phase differences* at different positions of a long circuit which yielded that the *difference* between two observed deflections of the dynamometer, which should be closely proportional to the phase difference at two positions of the circuit almost five miles apart, was less than 3/5 scale units out of 844; with respect to unavoidable observational uncertainties, this means that practically no phase difference at all could be detected. — In these observations, the oscillation period corresponded to 1/520 second, or to 260 turns per second of the little magnet.

Furthermore, from this theory, confirmed by practical tests, it follows that there is no such *velocity* that would be as important and meaningful for this kind of propagation as that claimed for the propagation velocities of sound and light in air and in the light aether, the exact measurement of which is among the most important tasks in physics because they have to be considered as true fundamental measurements for the exact knowledge of these media.

Should there be no such *velocity* serving as fundamental determination also for the motions propagating through the electric medium, then this leads to the question whether the theory would not offer another issue suited for a fundamental determination, leaving equilibrium out of consideration, which would have a similar meaning for the knowledge about the medium and replace that velocity in the present context.

According to the theory, such a topic should reveal certain *deviations* from Ohm's law which, with increasing *refinement of the conducting wires*, set in with very unsteady and rapidly changing currents. According to the theory the validity of Ohm's law, firmly established by experiment for steady currents and indeed also for variable currents, should hold only as far as a certain *coefficient, $c^2/r\mathfrak{E}$, depending on the nature of the electric fluid and of the conducting wire*, may be considered as vanishingly small. Whenever this coefficient, as is the case when the conducting wire is made finer, increases above a value that cannot be neglected compared with unity, then certain *deviations* of the manifestations of electric oscillations from the determinations derived from Ohm's law should become the more pronounced the faster the electricity oscillates. If these *deviations* could be observed and measured, they would lead to the knowledge of that *coefficient* which, depending on the nature of the electric fluid and of the conducting wire, is of utmost importance for the science of electricity.

The *physical meaning* of this coefficient is that of a ratio of the square of

the known velocity c (which determines in the fundamental law the ratio of the static and the dynamic part of the electric force) divided by the force that would be exerted by the total amount of positive electricity contained in one length unit of the conducting wire, assumed as concentrated in a point, on *1 milligram of the electric fluid* at the unit distance. Thus, this force would be determined if the *deviations* from Ohm's law, caused by the acceleration of the oscillation and refinement of the conducting wire, could be exactly observed and measured.

On the other hand, this force may be expressed as the *product* $r\mathfrak{E}$ of the amount of positive electricity, $\mathfrak{E}$, contained in a unit length of the conductor, expressed in electrostatic units, times the amount of electrostatic units, r, contained in *1 milligram of the electric fluid*, which, if $\mathfrak{E}$ and hence r were known, any electrostatically determined amount of electricity and likewise the masses of ponderable bodies could be expressed *in milligrams*.

If, as shown in a former treatise (see Transactions of the Royal Saxonian Society of Science, Vol. V, Sections 15 and 20),[10],[11] this amount of electricity, $\mathfrak{E}$, were determinable at least for certain conductors, namely, electrolytes like water, then the observation of oscillations would offer the *possibility* to determine the measure of electric masses like that of ponderable masses, even if the execution requires various preparatory work. This knowledge of the mass could never be obtained by means of *electrostatic* observations.

However, the execution of such a determination of the mass constitutes a new task that had to be reserved for a special treatise, even if the method had been completely established. This is a similar case like the magnetic measurements, the practicability of which in terms of absolute measures was demonstrated theoretically by Poisson, which, however, would have been fruitless without Gauss' investigations which led to the control of all details.[12]

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[10][Note by HW:] Wilhelm Weber's *Werke*, Vol. III, pp. 648 and 664.

[11][Note by AKTA:] [KW57, Sections 15 and 20, pp. 648 and 664 of Weber's *Werke*] and [KW19, Sections 15 and 20, pp. 48 and 65].

[12][Note by AKTA:] Gauss's work on the intensity of the Earth's magnetic force reduced to absolute measure was announced at the Königlichen Societät der Wissenschaften zu Göttingen in December 1832, [Gau32]. The original paper in Latin was published only in 1841, although a preprint appeared already in 1833 in small edition, [Gau41] and [Rei19]. Several translations have been published. There are two German versions, one by J. C. Poggendorff in 1833 and another one in 1894 translated by A. Kiel with notes by E. Dorn; a French version by Arago in 1834; two Russian versions, one by A. N. Drašusov of 1836 and another one by A. N. Krylov in 1952; an Italian version by P. Frisiani in 1837; an English extract was published in 1935, while a complete English translation by S. P. Johnson and edited by L. Hecht appeared in 1995; and a Portuguese version by A. K. T. Assis in 2003: [Gau33], [Gau34], [Gau36], [Gau37], [Gau94], [Gau35], [Gau52], [Gau75], [Gau95] and [Ass03].

The same holds also for other applications allowed by the theory of electric motion in conductors, for instance, of an exact determination of all processes in *telegraphs* or Rühmkorff's *machines*, because it is clear that the theory, first developed just for *circular* conductors, even if it were impeccable, would not be sufficient with respect to telegraphs or Rühmkorff's machines with completely different shapes of conductors, and that various investigations will be needed in order to control all details under such circumstances, like it is necessary to successfully perform such determinations.

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