On the Process of Hertz's Conversion to Hertzian Waves

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Abstract

This paper provides new elements for reconstructing HEINRICH HERTZ's conversion from an electrodynamic concept to a concept of field theory, a process that took place between September 1887 and February 1888. First of all, it is argued that, contrary to what one could deduce from HERTZ's own presentation in his *Untersuchungen* (or *Electric Waves*), paper N° 5 was actually written *after* the first publication of papers N° 6 and N° 7; this fact is illuminated by HERTZ's unpublished correspondence (Section 1). Following this reordering, an approximative process of HERTZ's conversion based only on his published papers is described (Section 2). Second, by complementing HERTZ's published *Erinnerungen* (or *Memoirs, Letters, Diaries*) with his unpublished *Versuchsprotokolle* (*Laboratory notes*), a much finer description of this conversion process is discussed (Section 3). It is finally concluded that HERTZ's idea of "air waves" belongs at the very end of this process, and was mainly attained through experimental hints found within HELMHOLTZ's theoretical framework.

1. On the chronology of Hertz's published papers

Hertzian waves established our concept of a Maxwellian electromagnetic field. However, the rationale of HERTZ's early experiments — as well as that of the man who suggested them, HELMHOLTZ — was electrodynamic, involving exclusively charges, currents, and their actions at a distance. In order to trace the process of HERTZ's intellectual conversion from that electrodynamic concept to his final concept of field theory — a process which occurred mainly between September 1887 and February 1888 — a close examination of the papers written by him in this period is crucial. Nonetheless, most of the historians[1] who examined

[1] See CAZENOBE — 1980, pp. 366 and 372–375; CAZENOBE — 1983, pp. 177–181, 191–197 and 204–207; JUNGNICKEL & MCCORMMACH — 1986, vol. 2, p. 87; RECHENBERG — 1988, p. 33; FRIEDBURG — 1988, p. 49.

them overlooked the fact that the order of HERTZ's papers, as they appear in his published *Untersuchungen*[2] of 1892, is not the same as the order in which they were written. This oversight leads to a serious misunderstanding of HERTZ's intellectual development.

1.1 The three papers of the winter 1887–1888

There are three papers corresponding to the period mentioned which, in their order in the *Untersuchungen* (and in the *Electric Waves*), are:

N° 5 "Ueber die Einwirkung einer geradlinigen elektrischen Schwingung auf eine benachbarte Strombahn" ("On the Action of a Rectilinear Electric Oscillation upon a Neighboring Circuit"),

N° 6 "Ueber Inductionserscheinungen, hervorgerufen durch die elektrischen Vorgänge in Isolatoren" ("On Electromagnetic Effects produced by Electrical Disturbances in Insulators"), and

N° 7 "Ueber die Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen" ("On the Finite Velocity of Propagation of Electromagnetic Actions").

These three papers were reprinted in the *Untersuchungen* as they were printed in Volume 34 of the *Wiedemann's Annalen*, and in their headings HERTZ correctly cites this volume. For papers N° 6 and N° 7, he refers there also to the *Sitzungsberichte der Berliner Akademie* of 10 November 1887 and 2 February 1888, respectively. Further, paper N° 5 is cited twice in each of the papers N° 6 and N° 7. Hence, naturally, the reader will infer that paper N° 5 had been written earlier, and at least before November 1887.

This way of dating paper N° 5 seems to be confirmed by HERTZ's presentation in the "Einleitende Uebersicht" ("Introduction") which he wrote in November-December 1891 as paper N° 1 for the *Untersuchungen*. In this "Introduction", his first successful experiments after the summer of 1887 are related to paper N° 5, and the following ones to paper N° 6.[3] Also, before the presentation of paper N° 7, HERTZ incidentally mentions "the preceding papers", obviously referring to papers N° 5 and N° 6.[4]

I argue that such dating could by no means be accurate. Actually, paper N°5 was first published in issue 5 of Vol. 34 of *Wiedemann's Annalen*, material for which was cut off on 15 March 1888. It is followed by papers N° 6 and N° 7 in issues 6 and 7 of the same volume, cut off, respectively, on 15 April and 15 May. However, these two papers had been presented at the Berlin Academy in November 1887 and February 1888, as already mentioned, and immediately published in the *Sitzungsberichte der Akademie*. This publication is a preliminary version, which for convenience I will call N° 6_{Ak} and N° 7_{Ak}. No such preliminary version of paper N° 5 was ever published.

[2] See HERTZ-*Untersuchungen*. I cite the pages of the German original edition, which practically agree with those of the edition of 1894 in HERTZ-*Werke*. For the convenience of English readers, I also cite the pages of the English translation of 1893, *Electric Waves* (*EW*).

[3] See *Untersuchungen*, p. 6, *EW* 5–6.

[4] See *Untersuchungen*, p. 7, *EW* 7. The original expression is "in den vorigen Abhandlungen" but has been translated by "in the paper referred to".

The later dating of paper N° 5 is clear from its heading in the *Untersuchungen*, where, was has been indicated, only *Wiedemann's Annalen* are cited and where the year 1888 is explicitly mentioned. In *Wiedemann's Annalen* the paper is dated at the end: "Karlsruhe, im Februar 1888". As I will show, it was written after papers N° 6_{Ak} and N° 7_{Ak}, and was sent to WIEDEMANN together with the new versions of N° 6 and N° 7 on 17 February 1888. The changes introduced in this new version can be identified by analytical comparison of the two published texts, but they will be better understood after reading HERTZ's synthetic description in his unpublished letters to WIEDEMANN. I just mention now that the references to paper N° 5 are, of course, introduced in these changes. HERTZ's presentation in the "Introduction" of 1891 should be considered didactic, not attempting an accurate chronology. There he follows the order of the experiments and cites the papers in which they are mainly described, without asserting anything about the order in which these papers were composed.

1.2 The idea of Hertz's Trilogy, according to his correspondence

HERTZ conceived the idea of composing the set of these three papers N° 5, N° 6 and N° 7 for publication in *Wiedemann's Annalen* after paper N° 6_{Ak} was already published, and when paper N° 7_{Ak} was still in press in the *Akademieberichte*. The idea is clearly described by HERTZ in a letter to GUSTAV WIEDEMANN, the editor of the *Annalen*, dated 24 January 1888. As HERTZ proudly explained to his parents. WIEDEMANN had written to him "asking whether he could also reprint [in his *Annalen*] my last paper [paper N° 6_{Ak}]".[5] It is on this occasion that HERTZ answers by proposing his idea of a kind of "Trilogy". Let us translate the main paragraphs of his letter:[6]

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[5] See the letter to his parents of 29 January 1888 in *Erinnerungen*, p. 250. The "also" must refer to paper N°4, dealing with what was later called the "photoelectric effect", that had been sent on 26 May 1887 to WIEDEMANN for publication in the *Annalen*, and with his permission on 1st June to HELMHOLTZ for a shorter publication in the *Akademieberichte* (see HERTZ's letter to WIEDEMANN of 26 May 1887 in DM, HN 3226, and HERTZ's Diary of 31 May and 1st June 1887 in *Erinnerungen*, p. 222). In the letter to his parents, HERTZ anticipates his answer to WIEDEMANN; it could be better translated: "That I still desired to revise it [N°6_{Ak}] somewhat, or rather to preface it by another one ["eine andere vorausschicken": N°5!]."

[6] DM, HN 3227. The original German text reads:

Karlsruhe, d. 24 Jan. 1888

Hochgeehrter Herr Geheimerath!

Für Ihre freundliche Anfrage, welche ich so eben erhielt, sage ich Ihnen meinen ergebensten Dank. ...

Die in den Akademieberichten stattgefundene Veröffentlichung hatte ich eigentlich als eine provisorische angesehen. Ich muss darin mich auf Gründe berufen, deren Veröffentlichung noch nicht erfolgt sei. Das darf natürlich bei einer endgültigen Veröffentlichung nicht stattfinden. Es war also meine Absicht, die Sache sogleich in vollständiger Form auszuarbeiten und mich dann an Sie zu wenden, Sie wissen mit welcher Bitte. Allein die Versuche haben mich sozusagen fortgerissen, da ich sehr interessante Fragen

Karlsruhe, 24 January 1888

Most Honorable Privy Councillor,

I express my respectful gratitude for your kind inquiry which I have just received. ...

Properly I had regarded the publication which appeared in the *Akademieberichte* as provisional. I must have referred there to arguments not yet published. This, of course, should never be done in a final publication. Thus it was my intention to elaborate the matter immediately in a more complete form, and then to address myself to you, you may imagine with what request. Only because the experiments carried me away, so to speak, since I saw facing me extremely interesting questions; thus I did not yet work out all that I wished, but I have recently sent to HELMHOLTZ a new article in which, as I firmly think, I provide the proof for a finite velocity of propagation of the electrodynamic actions, with a speed approximately that of light. I have just been informed by HELMHOLTZ that he will send the paper to press. ...

Thus I have thought out the following procedure as the best one, and you would do me a great favor if you approve of it. I would like to publish three short articles one after the other, or at least in successive issues, namely:
1. On the influence of a rectilinear electric oscillation upon a secondary circuit. (This contains the assumptions of the following articles which are published in the *Akademieberichte*, and it should take 8 to 10 printed pages.)
2. On the inductive actions of dielectric motions (about 14 pages).
3. On the velocity of propagation of the electrodynamic actions (about 16 pages).

The last two articles would essentially be the Communications to the

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vor mir sah, so dass ich zu jener Ausarbeitung noch nicht gekommen bin, sondern kürzlich an Helmholtz eine neue Abhandlung abgeschickt habe, in welcher, wie ich sicher denke, der Beweis für eine endliche Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen mit annähernd Lichtgeschwindigkeit, geliefert ist. Ich habe gerade von Helmholtz den Bescheid erhalten, dass er die Arbeit zum Druck einreichen werde. ...

So habe ich mir den folgenden Weg als den besten ausgedacht, und Sie würden mir eine grosse Gunst erweisen, wenn Sie denselben billigten. Ich möchte gern hinter einander oder doch in aufeinander folgenden Heften drei kleinere Abhandlungen haben nämlich
1. Ueber die Einwirkung einer geradlinigen elektrischen Schwingung auf eine secundäre Strombahn. (Dieselbe enthält die Voraussetzungen der folgenden, welche in den Akademieberichten veröffentlicht sind, und würde 8–10 Druckseiten füllen.)
2. Ueber die Inductionswirkungen dielektrischer Bewegungen (etwa 14 Seiten).
3. Ueber die Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen (etwa 16 Seiten).

Die letzteren beiden wären dann in wesentlichen die Akademieberichte, der schon erschienene und der noch ungedruckte. Ich würde die letzteren in Hinblick auf 1. etwas kürzen können, dafür möchte ich aber an manchen Stellen auch kleine Einschiebungen machen. Im wesentlichen aber würde ich sie aus gedruckten Ausschnitten zusammensetzen.

Ihr ergebenster
H. Hertz Dr.

Academy, what has appeared already and what is not yet printed. I may shorten a little the last articles in view of the first one, but in return I should like to make small insertions in some places, too. But I would, essentially compose them by cuttings from printed text.

Yours respectfully
H. Hertz, Dr.

HERTZ sent to WIEDEMANN the finished manuscript on 17 February 1888. His covering letter describes again the Trilogy and summarizes the changes in papers N° 6 and N° 7. Let us translate its main paragraphs:[7]

Karlsruhe, 17 February 1888

Most Honorable Privy Councillor,

Enclosed herewith please find the three papers about which I wrote to you last month.

That is to say:

I. A new manuscript "On the influence of a rectilinear oscillation, etc.", with 2 figures.

II. The paper already printed in the *Akademieberichte* on the electrodynamic action of insulators, with 1 figure. I have changed it, but only very slightly; essentially I have only replaced the addition on the action of light by another and I have attached the former one to the first paper, where it fits in better.

III. The manuscript of the paper "On the velocity of propagation etc,", with 1 figure. It has already been set in type for the *Akademieberichte*, and that is why the manuscript looks a little untidy, for which I beg your pardon. Here I have made some more small insertions and have also added a concluding

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[7] DM, HN 3228. The original German text reads:

Karlsruhe, d. 17 Februar 1888

Hochgeehrter Herr Geheimerath!

Einliegend erlaube ich mir nun, Ihnen die drei Arbeiten zu übersenden, von welchen ich Ihnen im vorigen Monat schrieb.

Es ist also:

I. Ein neues Manuscript "Ueber die Einwirkung einer geradlinigen Schwingung etc." mit 2 Zeichnungen.

II. Die schon in den Akademieberichten gedruckte Arbeit über die elektrodynamische Wirkung der Isolatoren, mit 1 Zeichnung. Ich habe doch nur sehr wenig geändert, im Wesentlichen habe ich nur den Zusatz über die Wirkung des Lichtes durch einen andern Zusatz ersetzt, und jenen der ersten Arbeit angefügt, wohin er besser passt.

III. Das Manuscript der Arbeit "Ueber die Ausbreitungsgeschw. etc." mit 1 Zeichnung. Es ist schon für die Akademieberichte gesetzt worden und daher sieht das Manuscript etwas unordentlich aus, was ich Sie bitte zu entschuldigen. Hier habe ich etwas mehr kleinere Einfügungen vorgenommen, auch einen Schluss hinzugesetzt. Sollte der Setzer lieber nach dem Druck setzen, so kann ich in einigen Wochen auch einen Separatabzug senden, bei den vielen kleinen Änderungen ist aber vielleicht kein Gewinn dabei.

...

Ihr ganz ergebenster
H. Hertz Dr.

section. If the typesetter should prefer to work from the printed paper, I could also send an offprint in a few weeks; but, there being so many small changes, perhaps nothing would be gained.

Yours most respectfully
H. Hertz, Dr.

These two letters leave no doubt that paper N° 5 was written after papers N° 6_{Ak} and N° 7_{Ak}, and that simultaneously those papers were modified. The chronology is therefore the following:

5 November 1887: HERTZ sent HELMHOLTZ the manuscript of paper N° 6_{Ak}, substantially the same as Chapter 6 of the *Untersuchungen*.[8]

21 January 1888: HERTZ sent HELMHOLTZ the manuscript of paper N° 7_{Ak}, substantially the same as Chapter 7 of the *Untersuchungen*.[9]

17 February 1888: HERTZ sent WIEDEMANN the manuscript of the Trilogy: paper N° 5 and the new versions of papers N° 6 and N° 7, as they appear in Chapters 5 to 7 of the *Untersuchungen*.

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[8] The only noticeable differences are:

— As he said in his second letter to WIEDEMANN, paper N°6_{Ak} finished with an addition "on the action of light" — new experiments on the photoelectric effect, for us here not very important — which was in place of the present last paragraph (*Untersuchungen*, pp. 133f, *EW* 105f). Hence, certifying by this paragraph (on some phase differences and some unsuccessful experiments to "establish a finite velocity of propagation of the electric forces") can be very reliable, but it was written up in February 1888.

— The three-line paragraph immediately preceding (*Untersuchungen*, p. 133, *EW* 105) on the difficulty of discusing quantitative relations, summarizes a nine-line paragraph of paper N°6_{Ak} on a quantitative conjecture which was proved experimentally wrong (when near to the electrodynamic balance a disturbing dielectric body is introduced, the angle the resonator has to be turned in order to reestablish equilibrium should be proportional to the dielectric constant minus one); only an order relation could be found (the greater dielectric constant, the greater angle).

— Of course, in paper N°6_{Ak} no references to paper N°5 could exist. Instead of the first reference (*Untersuchungen*, p. 103, *EW* 95) the paper N°3 of BEZOLD and paper N°2 were cited (in chronological order). Instead of the three-line paragraph containing the second reference (*Untersuchungen*, p. 106, *EW* 98) there was a seven-line paragraph which mentions "the totality of phenomena for an arbitrary position of the circuits against one another", and leaves them "for another occasion" (for paper N°5!).

[9] As mentioned in the second letter to WIEDEMANN, an important difference is:

— The addition of a "concluding section" not in paper N°7_{Ak}, that is, the one and a half pages of "Conclusions" (*Untersuchungen*, pp. 131f, *EW* 122f). There, especially in paragraphs 1 and 3, HERTZ expresses very clear ideas on field and waves, but they were composed in February 1888.

Among the "other small insertions", only the following are noteworthy:

— Modification of the four-line paragraph of *Untersuchungen*, p. 119 (*EW* 111). In paper N°7_{Ak} this paragraph was still shorter and could not refer to paper N°5, but only to "more reasons" of a phenomenological kind, there unexplained.

2. The process of conversion, according to the printed papers

Let us follow in chronological order the successive versions of HERTZ's three papers, from November 1887 through February 1888, paying attention to the successive steps of his conversion. We shall focus on what is explicit in HERTZ's conceptual formulations, taking care not to read into them what they do not contain explicitly. I will also briefly comment on the presentation of these papers that he wrote later, for the "Introduction" of December 1891.[10]

2.1 The paper of November: Inductive currents in dielectrics

In paper N° 6_{Ak}, as written up on 5 November 1887, HERTZ reaches the experimental conviction that in dielectrics can be produce what we call "displacement currents". Under the action of his very rapid electric oscillator, — as he writes there — "the quantities of electricity displaced in insulators by dielectric polariza-

- Insertion of the one-line sentence mentioning "special experiments" which prove that 60 meters of free wire were sufficient (on the same page, around the 12th line of the following paragraph).
- Insertion of the two paragraphs on "other ways" of distinguishing nodes from antinodes and on cutting the wire at a node (*Untersuchungen*, pp. 120f, *EW* 112f, the two paragraphs in between those referring to the "Notes at the end of book" 14 and 15; of course, such notes could not have been in either paper N 7_{AK} or in the version of paper N°7 in *Wiedemann's Annalen*).
- Insertion of the two three-line sentences on the conjecture of "a smaller velocity of propagation" in electrolytes, and on related experiments with a tube of "copper sulfate" (*Untersuchungen*, p. 121, *EW* 113, the two sentences immediately before and after the reference to Note 15).
- Insertion of the three-line sentence on "further modifications of the [interference] experiment — *e.g.* by carrying the wire beneath the secondary conductor" (*Untersuchungen*, p. 123, *EW* 115).
- Insertion of the last paragraph before the section on "Interference at Various Distances", and of the preceding three-line sentence (*Untersuchungen*, p. 125, *EW* 116f).
- Suppression of the heading "The electrostatic forces" ["Die elektrostatischen Kräfte"] which had the last four paragraphs now preceding the "Conclusions" (in *EW* correctly translated as three; *Untersuchungen*, p. 130, *EW* 121, after the fourth comment on the last table).
- Modification of the paragraph giving "the second reason" for a different velocity of the electrostatic and electrodynamic actions (*Untersuchungen*, p. 130, *EW* 122, the second of the paragraphs just mentioned). Its second sentence could not be a reference to paper N°5, and in its place was an eight-line explanation on how to determine the direction of the electric force. Instead of the beginning of the third sentence, there was a six-line description of the distribution of the electric force in free space, and its description at the end of the cyclical points was a little more phenomenological (not the forces, but the sparks, have there "same strength in all directions").

As indicated in the letter, these "many small changes" were not very important in HERTZ's opinion. Neither are they for our purpose, since between the two dates of the first version and later changes scarcely four weeks elapsed.

[10] See "Einleitende Übersicht", in the *Untersuchungen*, pp. 4–9, *EW* 4–9.

tion are of the same order of magnitude as those set in motion by conduction in metals".[11] These displacement currents, like the conduction currents, are made manifest by their inductive effects. The parallel between the two kinds of current is clearly emphasized in his main experiment with the induction balance, the equilibrium position of which is alike disturbed by the displacement current in a thick insulator and by the conduction current in a symmetrical, thin conductor.[12]

This conviction is the first step in HERTZ's conversion. It supported "the most promising electric theories", and "the intuitions proceeding from Faraday and Maxwell".[13] But MAXWELL's theory could also be reinterpreted from an electrodynamic point of view involving instantaneous action at a distance among charges and currents, and that seems to be the case with HERTZ's paper.[14]

It is noteworthy, however, that in this paper of November the electric forces were still considered:

(a) neither as "vectors" at every point of space,

(b) nor as "propagating in time" through it.

As far as (a) is concerned, it will be noted that HERTZ speaks of the "inductive action" ("Inductionswirkung") or "electrodynamic force"[15] and the "electrostatic force" that the primary circuit (the oscillator) exerts on the secondary circuit (the resonator). He does not consider these actions and forces as having a "direction" in space, but as acting in the direction of the different fragments of the secondary circuit with a "sign", which must be taken into account in the integration around the circuit.[16] Only when he intends to exclude electrostatic effects produced by the dielectric, does he speak of some electrostatic "lines of force".[17]

With regard to (b), it will be noted that the final addition, which recognizes some phase differences of the inductive action that inspire experiments "to establish a finite rate of propagation of the electric forces",[18] provides valuable testimony but, as already mentioned, it was written in February 1888. The only phase differences in the paper of November are related to the interference between some electrostatic oscillations and some resonant electrodynamic oscillations.[19]

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[11] *Untersuchungen*, p. 103, *EW* 96. See also p. 108, *EW* 101.

[12] *Ibidem*, p. 103, *EW* 96.

[13] *Ibidem*, pp. 102 and 108, *EW* 95 and 101.

[14] See *ibidem*, p. 170, *EW* 159. HELMHOLTZ had made this reinterpretation in 1870 in the framework of his general electrodynamics, in which he had proposed, in 1879 on behalf of the Berlin Academy, the problem now solved by HERTZ. On a more Maxwellian concept used earlier and later apparently forgotten by HERTZ, see AGOSTINO — 1975, page 295.

[15] The systematic translation in *Electric Waves* of "elektrodynamisch" by "electromagnetic" makes the distinction of these two concepts difficult.

[16] See *Untersuchungen*, p. 105, *EW* 98 (here a couple of times "Vorzeichen" ["sign"] has been translated by "direction", and is said to be "positive" or "negative"). HERTZ explicitly considers here the circuit as "unclosed" and placed in "arbitrary positions", see *ibidem* p. 105, *EW* 97, and the modification in p. 106, *EW* 98, mentioned at the end of Footnote 8.

[17] *Ibidem*, p. 112, *EW* 105.

[18] *Ibidem*, pp. 113f, *EW* 105f.

[19] *Ibidem*, pp. 107f, *EW* 100.

In the "Introduction" of December 1891, HERTZ describes in detail the process of this first step. His chronology is inaccurate,[20] but he depicts very plausibly the deep sources of his research, which grew from the Academy prize of 1879, and his fruitless initial approach to the problem. Both the sources and the initial approach prove the rationale of his work to be electrodynamic: on the action between currents in conductors or dielectrics.[21] HERTZ probably brings back to this time the whole revolution undergone in "the concepts and dogmas" of "the customary electric doctrine",[22] as he certainly antedates some of the experiments of paper N° 5, by presenting all as a prerequisite to the successful approach set forth in paper N° 6. In particular, his astonishment in observing the inductive action at "always greater distances", and his remark on the "not yet suspected reflections" belong to a later time. On the other hand, his view of the resonator as an "almost closed" circuit belongs to this time, as we will see.[23]

2.2 The paper of January: Propagation of the inductive action in time

In the paper N° 7_{Ak}, as written up on 21 January 1888, HERTZ proves that the inductive action is propagated in space with a "finite velocity". The proof is obtained from a careful study of the interferences between "the waves" (wavelike currents) propagated through a wire and "the direct action" (inductive action) propagated through the air at different distances of the oscillator. The results are displayed in four tables. They lead to him the conclusion that the inductive action propagates with a velocity greater that than of the current waves — in the ratio

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[20] According to HERTZ's presentation of this step: "The summer of 1887 was spent in fruitless endeavours ..." (*Untersuchungen*, p. 4, *EW* 4). But, as we will see in his Diary and *Protokolle*, from December 1886 until July 1887 HERTZ was very busy with experiments related to what later will be called the "photoelectric effect". The "fruitless endeavours" should be placed between 8 and 21 December 1886, and the successful ones up to 7 September 1887.

[21] The sources are well testified by the letters of 30 October 1887 to his parents and of 5 November 1887 to HELMHOLTZ (*Erinnerungen* pp. 232 and 234). The earlier letters of 11 and 19 August and 4 November 1879 to his parents repeat the old reaction of HERTZ to this prize and his writing up a paper on possible but not clearly successful approaches to the problem (*ibidem*, pp. 112 and 114). The autograph manuscript of this paper is preserved in the Science Museum in London, and has been partially published and should be published in full (O'HARA & PRICHA — 1987, pp. 122–128, and JAMES G. O'HARA's private communication). The fruitless initial approach of 1886 shows clear kinship with the second of the three types of experiments proposed in 1879. It introduced a dielectric body between the plates of a condenser connected to an induction coil. Its effect is weaker "but qualitatively very similar" to that obtained by the introduction of a fragment of conductor near to both plates of the condenser. Under the alternating electrostatic action, it should work as an elementary open current, able to induce other currents. This parallel between the rapidly alternating currents in conductors and dielectrics runs through HERTZ's corresponding calculations of 1879 (pp. 7–13 of the manuscript cited, kindly communicated by JAMES G. O'HARA) and grows from HELMHOLTZ's paper of 1870 (HELMHOLTZ, *Abhandlungen I*, pp. 611–628).

[22] "Begriffe und Lehrsätze ... der gewöhnlichen Elektricitätslehre", *Untersuchungen*, p. 5, *EW* 5.

[23] See question (B) in Section 3.1 below.

45/28 — but of the same order as the speed of light. This was valid only for the velocity of the inductive action or electrodynamic force. The velocity of the electrostatic action or force, however, was different and could be infinite.

This experimentally grounded conviction about the propagation of the inductive action in time constitutes a second, very important step in HERTZ's process toward the HERTZian waves, although he does not yet explicitly reach the end.

In the introductory paragraph, HERTZ points out the parallel between the electrodynamically active polarizations produced in a dielectric body (proved in paper N° 6_{AK}) and those that might be produced in the air or free space. If the latter actually exist, "we may conclude that ... electrodynamic actions must be propagated with a finite velocity".[24] As we will see, this conclusion is related to HELMHOLTZ's paper of 1870, in which the idea of hypothetical longitudinal and transversal "waves" and their connection with the "transversal waves" of the MAXWELL theory of light, are explicitly mentioned. Further, the very idea of interference seems to require implicitly two wave motions.

It is important to realize, however, that in this paper of January propagation of the electrodynamic forces was explicitly considered:

(c) neither as "waves" propagating through the air,
(d) nor as "evolution in time" of the force acting in every point of space.

In relation to (c), it will be noted that in this paper HERTZ uses again and again the term "wave" (more than 30 times), but exclusively to refer to wave currents propagating through the wire. They are reflected at the end of the wire and can produce stationary waves, whose visualized nodes and antinodes determine directly the wavelength. What propagates through the air, however, is called by HERTZ the "direct action", and its propagation is considered only along a "baseline" parallel to the wire.[25]

With regard to (d), it will be noted that, as in the earlier paper, HERTZ studies here the electric (electrostatic plus electrodynamic) forces by means of their effects in the resonator, which can be placed in three "basic positions". But now these forces are regarded as located at every point of space and having a definite direction there. He says, for instance, that in the first of these positions "the electric force is in all points perpendicular to the direction of the wire",[26] and then shows how to find "the direction of the force" in a meridian plane through the oscillator.[27] HERTZ, however, says nothing on the evolution in time of these oriented

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[24] *Untersuchungen*, p. 115, *EW* 107.

[25] Note that, if this propagation were instantaneous, as HERTZ's experiments seemed to indicate during a time, the idea of wave should be excluded. Remember that the conclusions at the end of the paper, and therefore the sentence in the third conclusion "that there actually are electrodynamic transversal waves in air", had been added for the new version a month later, on 17 February.

[26] *Untersuchungen*, p. 117, *EW* 109.

[27] Old version corresponding to *Untersuchungen*, p. 130, *EW* 122. This conception is now natural, since he is no longer considering the action of the varying forces of the oscillator on an oriented dielectric comparable to a conductor, but, according to the introductory paragraph, he is considering this action within an unoriented block of dielectric comparable to the air. There forces (or actions) and polarizations must have their own directions.

forces. The sparks of his resonators give only information about their mean direction and maximal strength in this direction. HERTZ rarely considers an instantaneous picture within the period of the oscillator.[28] Only once, in dealing with interference of electrostatic and electrodynamic forces, HERTZ mentions some cyclic points, in which he cannot detect the direction of the total electric force and imagines that "during each oscillation [it] passes through all points of the compass".[29]

In the "Introduction" of December, 1891, HERTZ puts forward a rational reconstruction of his second step. According to him, his guide would have been the final section of HELMHOLTZ's paper of 1870, which he cites explicitly here and whose three implicit assumptions for obtaining MAXWELL's equations from electrodynamic principles he enumerates: first, polarization changes in dielectrics (*i.e.* displacement currents) produce electrodynamic forces; second, electrodynamic forces produce changes of polarization in dielectrics; and third, both the air and empty space behave like dielectrics.[30] HERTZ's reconstruction considers his previous paper to prove the first assumption, which had been proposed by the Academy in 1879 along with the second one. Following a very unreliable chronology, his reconstruction places after that paper an attempt to prove the second assumption[31] and notes that although the first two assumptions would imply the propagation of waves with finite velocity in dielectrics, these implications would not be more surprising than the propagation of electric waves in wires.[32] Thus HERTZ reconstructs logically his view that the third assumption is the main point in the FARADAY-MAXWELL intuition, and that the evidence of "a finite velocity of propagation and waves in air" is the appropriate proof of this assumption. This was, according to HERTZ's reconstruction, the program of research successfully accomplished in paper N° 7. But the intimate connection between "finite velocity" and "waves in air" which this rational reconstruction imposes is absent, as we have seen, for the paper of January, and was absent, as we shall see, from his research program.

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[28] "Let us take under consideration an instant in which the plate P has its largest positive charge", *Untersuchungen*, p. 123, *EW* 115.

[29] *Untersuchungen*, p. 131, *EW* 122. I will return to these points in the context of the third step; see Section 3.3 and question (G) below.

[30] *Untersuchungen*, pp. 6–7, *EW* 6–7. Notice that here, and explicitly in a following footnote, "air" ["Luft Raum"] and "empty space" ["leerer Raum"] are used by HERTZ "as synonymous, inasmuch as the influence of the air itself in these experiments is negligible".

[31] After concluding the experiments of paper N°6_{Ak} and sending it to the Academy on 5 November 1887, HERTZ was obtaining, on 7 November, stationary waves in wires. There is no space here "to think for some time" and "to cast closed rings of paraffin". HERTZ is probably placing here the "ring of paraffin cast for dielectric experiments" one year before at the beginning of the "fruitless endeavors" of 8 December 1886. See Diary of these days in *Erinnerungen*, pp. 232–234 and 216.

[32] Curiously, this last sentence has been skipped in the English version. In *Electric Waves*, p. 7, line 13, after "differ widely from that of light" should be added: "But that could not surprise us very much, no more, perhaps, than the well known fact that the electric excitations are propagated in wires with a greater but finite velocity."

On the other hand, HERTZ's account is very reliable when he distinguishes clearly a direct discovery of waves and stationary waves in wires, from a circuitous one of finite velocity in air. Perhaps he dramatizes too much his objective, at the end, of proving "that Maxwell's theory was false". Also the account is too troubled by the problem of the different velocities of propagation in a wire and in air, which was not solved even in December, 1891.

2.3 The Trilogy of February: Electrodynamic waves in space

I will discuss now the parts of the Trilogy completed on 17 February 1888, namely paper N° 5, and the changes in papers N° 6 and N° 7, particularly their final additions.

In paper N° 5 HERTZ presents "the totality of the phenomena that appear for an arbitrary position" of the resonator against the oscillator. This fills a gap in the foundations of paper N° 6_{Ak}, which had then been left "for another occasion".[33] HERTZ must have known these phenomena partially before writing papers N° 6_{Ak} and N° 7_{Ak}, but now he is able to present them both in a more complete way and according to a more advanced concept.

HERTZ, indeed, presents the facts within the framework of a simple theory which, as he recognizes, they are independent of. This theory, contrary to assertions (a) and (d) above, assumes "at every point" an electric force with a definite "direction," which "fluctuates up and down".[34] The "force components" and the "lines of force", both electric and magnetic, are explicitly considered. Particularly important is the method of fixing the direction of the electric force, which is used to explore it at "great distances" in a meridian plane through the oscillator. The results are even sketched in a figure,[35] with a kind of electrostatic lines in the vicinity, parallel lines at a distance, and cyclic points in between. All that, contrary to assertion (c) above, provides now a clear impression of cylindrical waves propagating in a three-dimensional space. But, as we will see, these results belong to experiments and to a concept which are far more advanced than those HERTZ described and held in papers N° 6_{Ak} and N° 7_{Ak}.

The half-page addition at the end of paper N° 6, which replaces the old addition on the photoelectric effect in paper N° 6_{Ak},[36] is intended to link papers N° 6 and N° 7. As mentioned above, with this addition HERTZ provides a clue for

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[33] This was announced in paper N°6_{Ak} (in the early version of the paragraph in *Untersuchungen*, p. 106, *EW* 98, in which paper N°5 is cited), as mentioned at the end of my Footnote 8 above. See also HERTZ's letter of 24 January 1888 to WIEDEMANN, in Section 1.2 above.

[34] It is noteworthy that in order to express for the first time the idea of oscillation of forces in space, he does not use here the German words (schwingen, oscilliren = oscillate), which he had used for the oscillation of charges in circuits, but a new one (hin und her schwanken = fluctuate up and down). *Untersuchungen*, p. 89, *EW* 82 (where it is simply translated: "... the electric force at every point varies ...").

[35] *Untersuchungen*, p. 99, *EW* 91.

[36] *Untersuchungen*, pp. 113–114, *EW* 105–106. See above HERTZ's letter to WIEDEMANN of 17 February, paragraph II.

reconstructing the intellectual process which had led him, three months before, from his experiments on the dielectric currents to a test on the possible delay in the propagation of inductive actions.

The addition of one and one half pages at the end of paper N° 7 displays the "conclusions" that HERTZ was ready to publish in February 1888, as the colophon of his Trilogy.[37] Conclusions 1 and 3 are specially important for our purposes. In Conclusion 1, in contrast with point (a) above, HERTZ now establishes vividly the "independent existence of electric forces in space", which is consonant with FARADAY's concept. In Conclusion 3, in contrast with point (c) above, HERTZ clearly establishes the "actual existence of electrodynamic transversal waves in air". This is the first time that his expression of "waves in air" appears in print. But these conclusions are written up on 17 February 1888, only ten days before he will begin the experiments leading to paper N° 8, "On Electromagnetic ["elektrodynamische"!] Waves in Air and their Reflection".[38]

In the "Introduction" of December 1891 HERTZ, as mentioned above, leads his reader to regard paper N° 5 as prior to papers N° 6 and N° 7, and with his rational reconstruction binds together "finite velocity" and "waves". He is more reliable when the confirms the addition at the end of paper N° 6 speaking only of "finite velocity", and when he relates the first experiments on the reflection of the electric force not with paper N° 7 but with paper N° 8.[39]

3. The process of conversion, according to the Protokolle

Judging by the published papers, we have found the process of HERTZ's conversion as proceeding through three steps: "induction by dielectric polarization", "finite velocity of inductive action" and "wave propagation of electric forces". This process, however, can be analyzed in much greater detail by exploring other sources which HERTZ did not intend to publish, mainly his Diary and his *Laboratory notes*. His Diary is well known, as well as are most of HERTZ's letters to his parents and to HELMHOLTZ.[40]

On the contrary, HERTZ's *Laboratory notes* or *Versuchsprotokolle*, which for simplicity I will call *Protokolle*, are not yet so well known.[41] They amount to

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[37] *Untersuchungen*, pp. 131–132, *EW* 122–123.

[38] See the diary from 27 February 1888 onwards in *Erinnerungen*, p. 252.

[39] *Untersuchungen*, pp. 8 and 11, *EW* 9 and 11.

[40] See their excellent bilingual edition, HERTZ — *Erinnerungen*, that I shall constantly use and call simply *Erinnerungen*.

[41] Only two of their pages, namely those of my Figures 2 and 3, had been reproduced by GERHARD HERTZ on the 100th anniversary of the discovery of electromagnetic waves; see HERTZ, G — 1988a (Figures 6 and 9) and HERTZ, G — 1988b (Figures 9 and 10). With his kind permission, the four pages of my Figures 1–4 were first reproduced in the Spanish book HERTZ — 1990, pp. 184–188. A microfilm of the complete original manuscript has been deposited in the Archives of Karlsruhe University. I hope that a critical edition with English translation will soon be published.

23 autograph pages in old German script, with many indications of dates, sketches of figures and fragments of tables. Their contents can be roughly classified as follows: 3 pages on the electric effects of light, 1 page on the inductive effects of dielectric polarization, 17 pages on the finite velocity of inductive forces, and 2 pages sketching wave propagation of the electric force. In this section I will deal only with these fragments of the manuscript which, if contrasted with the corresponding fragments of the Diary, yield valuable clues on HERTZ's conversion.

3.1 First step: Dielectric currents without field evolution

The first three pages of the *Protokolle* deal with electric effects of light and are not relevant here. They only confirm what we have already learned from his Diary and correspondence: HERTZ was very busy with further experiments on light during this summer of 1887, even after sending off his manuscript, "On an effect of ultra-violet light ...", at the end of May and until his departure for holidays at the end of July. During that summer he could not have had time left for experiments on dielectric currents, which were fruitless because he had not yet found appropriate positions of the resonator.[42] It would be interesting to learn when the experiments began to succeed and how much had to be known first about the way of placing the resonator.

Hence we can ask the following:

(A) When did HERTZ discover the "equilibrium position" of his electrodynamic balance, so crucial for paper N° 6_{Ak}?

(B) How much did HERTZ know of the "contents of paper N° 5" before he could prove the effects of dielectric currents with that balance?

(C) Did these known contents imply a concept of "field of force" and its evolution in time, that is more elaborate than that which appears in paper N° 6_{Ak}?

The fourth page of the *Protokolle*, the only one that records the experiments on dielectric currents, provides partial answers to these questions. In complete agreement with the Diary, this work "on rapid oscillations" begins with the date "P. d. Sept. 7" (apparently a post-script) and ends two months later when HERTZ sent his finished paper N° 6_{Ak} to HELMHOLTZ on "Nov. 5". Immediately above this last entry and also in agreement with the Diary, the performance of the "first experiments" and the attainment of "clear results" by means of "a heap of books and an asphalt log" is recorded with date "Oct. 5".[43] Apart from those three dates, this page of the *Protokolle* is not chronologically clear.[44]

[42] On HERTZ's inaccurate chronology in this point on the "Introduction", see Section 2.1 and Footnote 20 above.

[43] "Bücherhaufen und Asphaltklotz". Compare with the Diary through these dates in *Erinnerungen*, pp. 228–232. Note that the "first drawing" and the "second drawing", made "at home" on the two Sundays, 18 and 25 September, are not related to his research but to his teaching. They are very good drawings for visualizing "Elliptical coordinates" and "Spherical functions", which are preserved in DM, HN 3266 and 3265) and are signed by HERTZ on 18 and 27 September 1887. The "Spherical functions" are also mentioned in his Diary on 29 September.

[44] Between "P. d. Sept. 7." and "Oct. 5." only the date "Oct. 10." is added at the

By use of the information of the Diary, question (A) can be answered as follows. The position of "equilibrium" for the resonator, as well as its perturbation, if a conductor or the human body is approached, must have been found between 8 and 12 September 1887. The "compensation" of the perturbations produced by thin conductors and thick dielectrics must have been conceived between 17 and 23 September, and actually were tested about the 5th or 6th of October. Between 11 and 31 October HERTZ made the "control experiments".[45]

As for question (B), however, only the fourth page from the *Protokolle* can provide an answer. Under the date "P. d. Sept. 7" and with the title "Generalities of the phenomena" HERTZ includes a certain short treatise on diverse positions of the "induced circuit". The positions are classified under two kinds: "A. ... perpendicular to the meridian plane", and "B. ... lying in the meridian plane". About the second kind he mentions only the greater "variety of phenomena", but of the first one he provides very precise information. He begins by describing the "equilibrium" position: the resonator perpendicular to the meridian plane through the oscillator, with its spark gap in this plane. In this position "the sparks disappear". They appear when the spark gap is removed from the meridian plane by turning the circular resonator around its axis, and they appear more or less vividly according to the different orientations of the resonator, remaining perpendicular to the meridian plane. HERTZ records here also his conviction that, because of its spark gap, the resonator must be considered as an open circuit.[46] No further word is said in the *Protokolle* on the positions of the resonator, and absolutely nothing is said on the distribution of the electric forces at great distances and its wave aspect, which will be described in paper N° 5.

Question (C) is more problematic, for the *Protokolle* define here explicitly the "direction" in space of "the magnetic force" and of "the electric force". Nevertheless, these forces are presented as being stationary, with no change in time.[47]

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margin and introduces a dozen lines in smaller writing, which probably have been inserted in a space previously left blank. Seven of those lines deal with "other positions" of the secondary circuit. The last five have the title "sensibility in the compensation" and are a kind of memorandum of paper N°6_{Ak}: from the disturbance of the equilibrium by the presence of a human body and the perturbations introduced by a conductor or a dielectric, to the "compensation" between both perturbations and the reply to possible objections.

[45] See in the Diary the entries for those days and the letter of 25 October, in *Erinnerungen* pp. 228–232.

[46] In the first seven lines inserted on "Oct. 10." he clearly gives experimental proofs that "the oscillation is a proper one of the whole circuit", and that "the insertion of the spark gap alters the closed circuit". This open character of the "almost closed" secondary circuit is well emphasized in paper N°6_{Ak}; see Section 2.1 and Footnote 16 above. HERTZ points out here also that in this way "the phenomena for other positions" become intelligible. That could be the origin of the future "simple theory" in paper N°5 (see Section 2.3 and Footnote 34 above) but in the *Protokolle* there is not a word on that theory.

[47] The fact that in the "equilibrium" position the sparks disappear means, according to the *Protokolle*, that: "1) The magnetic force is everywhere perpendicular to the meridian plane. 2) The electric force ... lies in the meridian plane." And after noting

It is noteworthy that this clear concept of directed forces standing in space does not appear at all in paper N° 6_{Ak}, as indicated in assertion (a) above.

3.2 Second step: Propagation in time without waves

The bulk of the *Protokolle* — 17 of their 23 pages — is devoted to the record of the experiments related to paper N° 7_{Ak}. These pages are clearly dated from "7 November" to "30 December 87". Further, the last and most important experiments, those recorded from "Saturday, the 17 December" onwards are carefully numbered from 1 to 64. The experiments begin by establishing stationary waves in wires. Then they plan — with or without success — to detect interferences in the resonator between the action propagated through the wire and the direct action, trying for these purposes many arrangements, but chiefly the three "basic positions" described in paper N° 7_{Ak}. Finally, they yield the data tables which were published in the paper as a clear proof of the finite velocity.

Hence we could propose a new set of questions:

(D) When and how did HERTZ begin to "search for a finite velocity" of propagation of the inductive action in air?

(E) Which were the "first favorable results" that convinced him of this finite velocity?

(F) Did HERTZ speak of "air waves" when describing those experiments on interference?

In complete agreement with the Diary, on 7 November 1887 HERTZ observes "stationary oscillations in straight stretched wires ... all through the laboratory". Through 10 November he seems very busy studying this phenomenon with different wires and oscillators and measuring the corresponding wavelengths.[48] Nothing as yet is recorded, either on the velocity of propagation in air or on interferences.

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that the sparks are of different intensity for different directions of the resonator perpendicular to the meridian plane, the *Protokolle* follow with: "The direction in which they become maximal is the direction of the electric force, the vanishing direction is perpendicular to it." These results can be obtained by symmetry considerations, but they presuppose the conception of forces everywhere in the space, although they are considered stationary in fixed directions.

[48] The experiment of 8 November is illustrated in a significant figure representing the oscillator of paper N°6_{Ak} (see Figure 24 in *Untersuchungen* p. 104, *EW* 97) and a secondary circuit terminated by metal pieces, in which stationary waves are electrostatically induced with three visualized nodes at distances of 300 cm (half the wavelength). On 9 and 10 November the experiment is successfully repeated with wires of iron and copper of various thickness (finding the same nodes), and also unsuccessfully with a pipe of copper sulfate. Finally, on the "10 November evening" the experiment is repeated with apparatus at half the scale, which yield half the wavelength. Everything perfectly agrees with the Diary as long as the annotations written there (by HERTZ's oversight?) in the places of 8 and 10 November are supposed to correspond to 9 and 11 November. To palpate stationary waves in wires on 7 and 8 November "almost as ... a vibrating string", should constitute the new "most beautiful experiments" (see ELISABETH's letter of 9 November, and first paragraph of HERTZ's letter to HELMHOLTZ of 8 December, in *Erinnerungen*, pp. 234 and 238).

As for question (D), the first attempts to measure the velocity of propagation in air seem to be some "Vain experiments" performed on 11 and 12 November, and some "Other likewise negative experiments" performed on 17 and 18 November. The decisive experiments were performed in the second half of December.

About the very first attempt, there is only one line in the *Protokolle*: "11–12 Nov. Vain experiments to determine the velocity of propagation through air".[49] This entry proves that at the beginning HERTZ intended to measure the concrete value of the speed. According to the Diary, those experiments deal with "interferences between the direct actions and those transmitted along wires" and they "succeed", but they are in vain because, "contrary to expectations, the result gives infinite propagation". We do not know any more details on this experiment on interference. Nevertheless, it could be in HERTZ's mind from the very beginning of the experiments about waves in wires.[50]

We do know in far greater detail the second attempt. Under the title "18 Nov. 87. Experiments on propagation through air", the *Protokolle* record an experiment intended to "observe a phase shift ... due to the delay through the air" of the inductive action when it propagates from the oscillator to a parallel conductor and back. The experiments are illustrated by a significant figure which reminds us of the electrodynamic balance used for paper N° 6_{Ak} but in which the equilibrated pieces are two conductors at a great distance from the oscillator.[51] Those experiments surely are the same as the "other experiments on finite velocity of propagation of the actions" which are vaguely recorded in the Diary for 17 and 18 November. They "yielded equally negative results" and, "very carefully repeated", they occasioned HERTZ "thoughts about Maxwell's theory".[52] Consequently, we can locate at this time the "experiments without success" which, according to HERTZ's testimony in the addition to paper N° 6 of February 1888 and in the "Introduction" of December 1891, led his intellectual process from the experiments on dielectric currents to the idea of finite velocity through air, but surprisingly did not lead either to the first or to the definitive attempt to prove it.

According to the Diary, HERTZ made no experimental progress during the four weeks following 18 November, in his careful repetition of the "other experiments". One annotation says that he "experimented, without real enthusiasm", and another gives the reason.: "Lectures occupy me completely." But he did some "theoretical work ... according to Maxwell's theory", and developed a "theory of

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[49] "11–12 Nov. Vergebliche Versuche die Ausbreit[un]gsgeschwindigkeit durch dem Luftraum zu bestimmen." This line is in smaller writing and might have been inserted later in a blank space.

[50] See the Diary on 10 and 12 November (probably corresponding to 11 and 12 November, according to the Footnote 48 above) in *Erinnerungen* p. 234. That on 9 November HERTZ "already had material for another paper" and that the week before Sunday, the 13 November, something failed, "on whose success he almost certainly counted", is not easy to understand if he had not conceived these velocity experiments from the very beginning.

[51] HERTZ makes the "conjecture that the interference takes place" when the conductors are separated from the oscillator. But in fact "it does not take place, ... not even for 1.5 m", *i.e.* for a distance of a quarter wavelength.

[52] See in the Diary the entries for these days in *Erinnerungen*, p. 238.

propagation of waves in wires". In his letter to HELMHOLTZ of 8 December, he deals mainly with those waves in wires and with their rather small velocity, but also with the interference between their actions and the "actions transmitted through air" and with the too high velocity of the latter. He very likely is thinking of his "vain experiments" of 11–12 November when he acknowledges: "I must repeat these experiments, and hope to be able to refine them". The repetition and refinement start on 16 December by "filling the gaps".[53]

The *Protokolle* confirm also the interruption of the experiments during the four weeks after 18 November, postpone their resumption to the 15 December, and disclose what is meant by "filling of the gaps". A sheet with this later date shows a lot of sketches and some lines of explanation on concrete "positions" of the resonator and its spark gap, in order to "find interference of the action of the wire and the direct action". On the recto the most significant arrangement for paper N° 7_{Ak} is clearly introduced: the trial in intermediate positions between those which in the paper are called the "first basic position" and the "second basic position", and are respectively sensitive to the "direct action" and to the "waves in the wire". On the back of the sheet unexplained sketches indicate different forms of deviating the wire around the resonator which may correspond to the other significant arrangement of paper N° 7_{Ak}: the "third basic position", sensitive to the electrodynamic action and not to the electrostatic action of the oscillator. But the interference seems to be sought for the moment at only one distance, let us say, at the "zero-point" of the printed paper. The phase of the wire waves at this point is nevertheless changed by "lengthening the wire backwards", that is, between the points *mn* of the figure in the printed paper.[54]

In agreement with the Diary, the *Protokolle* record, with the dates 17, 21 and 22 December, as many as seven pages of experiments, carefully numbered from 1 to 43. They concern the observation of the positive or negative character of the interference, using alternatively the two significant arrangements, and varying in each the phase of the wire waves by "inserting backwards" more and more half meters of wire. The "radical experiments" in the Diary of 22 December are called in the *Protokolle* "more accurate experiments than before on propagation in air". Their novelty consists in observing the interference at different distances from the oscillator, every half meter from the zero-point until advancing $8\frac{1}{2}$ meters along the wire. HERTZ is using the first arrangement, and for each distance he notes simply a "+" if the secondary sparks decrease with the rotation of the resonator from the first position to the second one in a certain direction, "−" if they decrease with the rotation of the resonator in the contrary direction, and "0" if they remain indifferent to the rotation. The "Scheme of the results", later labelled "Table 1" is almost the same as the first of the tables published in paper N° 7_{Ak}.[55] In the

[53] See the entries for these days in the Diary and the letter to HELMHOLTZ in *Erinnerungen*, p. 238.

[54] See *Untersuchungen* pp. 117–118, 123–124 and 116; *EW* 109–110, 114–116 and 108.

[55] See *Untersuchungen* p. 126, *EW* 118. The column of results corresponding to a distance of $8\frac{1}{2}$ meters is marked in the *Protokolle* with a question mark and was suppressed in publication. There is a small misprint in the last line of the table — as printed in

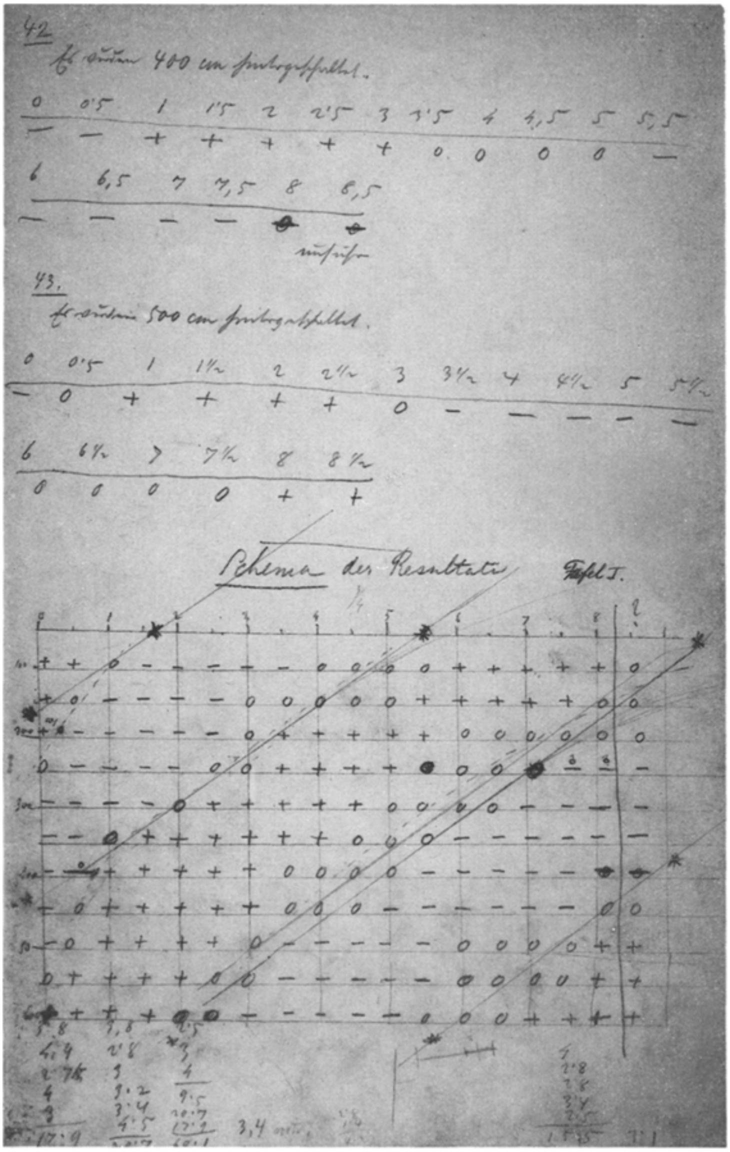

Fig. 1. Page of HERTZ's *Protokolle* corresponding to 22 December 1887. HERTZ could not be convinced of a finite velocity of propagation from the data so far obtained (which correspond only to five lines of the "Table 1" in the lower half of the figure).

Protokolle this table is written at the end of the last page corresponding to 22 December, but some data clearly corresponding to the next day have been included there, as can be seen in Figures 1 and 2.

Wiedemann's Annalen, in the *Untersuchungen* and in *Electric Waves* —; this line should finish "0 0 0 + + +", as is recorded in the *Protokolle* and is printed in paper N°7_{Ak}.

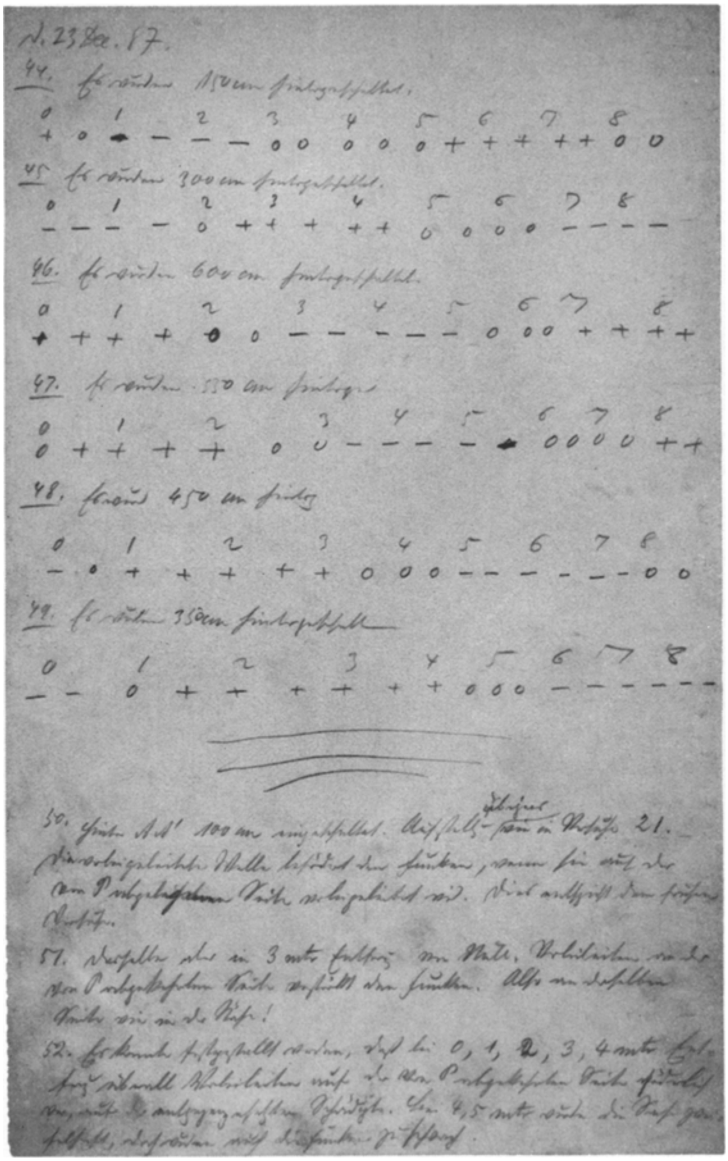

Fig. 2. Page of the *Protokolle* dated 23 December 1887. HERTZ obtained "an indication of the finite velocity" with these new data (part of which complete the "Table 1" in Figure 1, and part of which correspond to a new experimental arrangement).

The interesting point, related to question (E), is why the results of the "radical experiments" 36–43, obtained on 22 December, were not yet decisive to establish the finite velocity of propagation in air. The solution of this point could also explain HERTZ's pessimism toward the "most promising electrical theories", when he writes to his parents on 23 December (presumably in the morning): "there is no arguing with nature", and "once again the experiments seem all too clear to me".[56] These experiments yield only the results tabulated in five of the eleven lines of "Table 1": the lines corresponding to 100, 200, 250, 400 and 500 cm of inserted wire. As can be seen in Figure 1, a calculation below Table 1 in the *Protokolle* searches for the mean value of the five numbers 4, 2.8, 2.8, 3.4, 2.5, which probably are the first half lengths of interference, or distance between the first two zeros for these five experiments of 22 December. The mean value comes out exactly 3.1, which is very close to the half length of the wire waves, then estimated as 3 meters. Therefore the inductive action must be propagated instantaneously through air!

Now we can properly answer question (E). According to the Diary, on 23 December in the afternoon HERTZ did obtain "an indication of the finite velocity of propagation of the inductive action". He mentions it in a letter to his parents (dated on 26 December, presumably in the morning), as "a great gift" obtained "on the night before Christmas". As can be seen in Figure 2, one page of the *Protkolle* records under the date 23 December experiments 44–52.[57] The "radical experiments" 44–49 complete Table 1, so that the mean value of the half length of interference becomes longer. The infinite velocity can be excluded by the plausibility arguments published below this table.[58] Experiments 50–52 observe the interference by the complementary method that excludes the electrostatic action: the wire is deviated and placed close to the resonator in its "third basic position". The set of those new results will be tabulated in "Table 2", the third table published in paper N° 7_{Ak}.[59] The preliminary results of 23 December correspond only to the first line of this table, but they are another "indication of the finite velocity of propagation".

3.3 *Third step: Air waves and forces running around*

According to the Diary, after Christmas HERTZ performed many experiments through which he "obtained confirmation" of the earlier results (26 December, afternoon), and "observed the effect of the electrodynamic waves up to 14 m" (28 December); these experiments ended on 31 December when he was "weary of experimenting".[60] The last four pages of the *Protokolle* explain in detail twelve more experiments, which correspond to each day from the 26th to the 30th of December, and are recorded under the numbers 53 to 64. They are very interesting both, as a last answer to question (E), determining which experiments led HERTZ

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[56] See *Erinnerungen*, p. 240.

[57] This page of the *Protokolle* has been partially interpreted in HERTZ, G — 1988a, p. 44, Figure 6.

[58] See *Untersuchungen*, p. 127, *EW* 118. As is there indicated, the principal reason for the increase of this mean value is that in this completed table more second half-lengths of interference can be estimated. In the *Protokolle* another mean value of 14 numbers is calculated with result 3.4 (see Figure 1).

[59] See *Untersuchungen*, p. 128, *EW* 120 above.

[60] See *Erinnerungen*, p. 246.

to conclude that the inductive action propagated in air at a finite velocity, and in answer to question (F), about how HERTZ began to conceive and describe this propagation as "air waves".

Experiments 53 to 56 correspond to 26 and 27 December. They finish the observation of interference in the position which eliminates the electrostatic action, with the complete "Table II" exactly equivalent to the third table published in N° 7_{Ak}.[61] After this table, the annotation of 27 December concludes: "The velocity of the induction wave is therefore of a magnitude similar to that in wire. Proportion around 3:2." It ends with an argument that "proves the air wave to be the faster".[62] Leaving aside the problem of the apparent difference of velocities, we should enjoy the expressions "induction wave" and "air wave" ("Inductionswelle" and "Luftwelle"), which are doubtless the first used by HERTZ to refer to Hertzian waves.

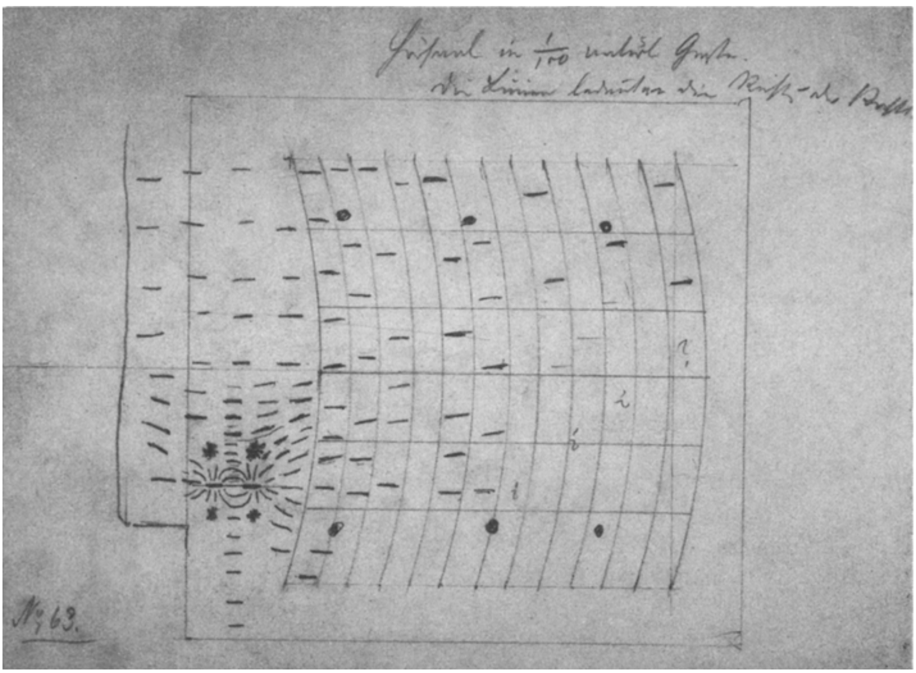

Fig. 3. Drawing of the *Protokolle* dated 29 December 1887. The lines give the mean direction of the electric force, in a meridian plane of the oscillator "throughout the whole classroom".

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[61] From the Table II in the *Protokolle* a sixth column — corresponding to a distance of 5 meters and full of question marks — has been suppressed, and the symbols + and — have been systematically interchanged in paper N°7_{Ak}, as in the *Untersuchungen*, p. 128, *EW* 120 upper table.

[62] "Die Geschwindigkeit der Inductionswelle ist also von ähnlicher Grösse wie die in Draht. Verhältniss etwa 3 : 2 ... Dass ... beweist, dass die Luftwelle die schnellere ist."

Experiments 57 to 62 correspond to 28 December. They provide a more precise measurement of the wavelength in wire, and seek to analyze the interference in air between electrostatic and electrodynamic actions. The annotation of this day concludes (speaking of course of half lengths): "Wavelength in the wire 2.8 meters, of the induction waves in air 4.5 meters, of the electrostatic action $= \infty$."[63] I will have more to say about experiment 63 on 29 December. Experiment 64, the last in the *Protokolle*, corresponds to 30 December. It succeeds in obtaining the earlier observations of interference, those of 22 and 23 December, up to a distance of 12 meters. Thus Hertz obtains "Table III", which contains the second table published in paper N° 7_{Ak}.[64] As indicated there, this table, especially if combined with the table of 27 December, provides a clear proof that the velocity is finite.

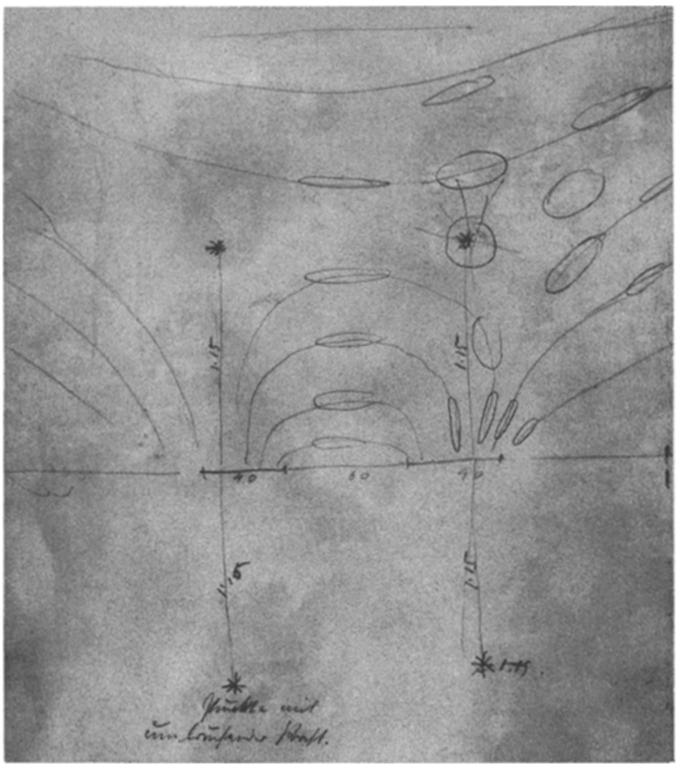

Fig. 4. Detail and interpretation of the drawing in Figure 3. The circle and the ellipses indicate the evolution of the electric force, "running around" during a period of the oscillator.

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[63] "Wellenlänge im Draht 2,8 mtr, der Inductionswellen in Luft 4,5 mtr, der elektrostat[ischen] W[irkung] $= \infty$."

[64] See *Untersuchungen*, p. 127, *EW* 120 below. In Table III of the *Protokolle* there is only one more line corresponding to 175 cm of inserted wire, and many indications about its having been "well observed".

The annotation of 29 December on experiment 63 reads: "Followed spreading of the action throughout the whole classroom towards all sides. Result according to drawing. / Followed also the action up to 14 meters of distance. Observed also the protective action ['Schutzwirkung'] of a zinc sheet." The drawing alluded to is on another sheet of the *Protokolle*, reproduced in Figures 3 and 4. In the upper part of Figure 3 can be read: "Classroom to 1/100 of natural size. / The lines mean the direction of the force."[65] It is the central part of this drawing which was included by HERTZ in paper N° 5, although, as we see, the subject of air waves comes clearly later than the topics of papers N° 6 and N° 7.[66] Figure 4 gives a detail of the waves in the preceding figure. Under one of the points marked with an asterisk can be read: "Points with force running around." ["Punkte mit umlaufender Kraft."] Thus, the circle and ellipses added to the drawing properly mean the variation of the electric-force vector during a period. This seems to be the first dynamical vision of the field. It renders precise the stationary vision of the mean value, the only one drawn in the preceding figure and the only one properly observed by HERTZ.

4. Conclusion

HERTZ's experience of conversion is of paramount importance for the history of physics — in some way it recapitulates ontogenetically the conceptual phylogeny of the field theory. The understanding of HERTZ's Trilogy and some data from HERTZ's unpublished *Laboratory notes* have allowed us to reconstruct this process more closely. The main points of this reconstruction are:
(α) HERTZ's idea of "waves in space" came at the very end of his experiments referred to in the Trilogy, and
(β) HERTZ was led to this idea mainly by some experimental hints found within HELMHOLTZ's theoretical framework.

The first step that led to the proof of inductive currents in dielectrics is clearly HELMHOLTZian in character — by both its old sources and its initial approach. The experimental hint for this step was doubtless the new possibilities of his very rapid electric oscillations. The related paper N° 6_{Ak} (written up on 5 November 1887) makes no mention of electric forces standing in space or propagating in time — although the *Protokolle* of this time speak of the direction in space of such stationary forces.

The second step, leading to the proof that "inductive action" propagates in time, also comes from old HELMHOLTZian sources and was conceived in the electrodynamic framework of currents acting on a resonator. An experimental hint was the phase delay guessed at during the preceding experiment — although the test suggested was neither the first one nor a definitive one. A new experimental hint

[65] This page of the *Protokolle* has been interpreted in HERTZ, G — 1988a, p. 47, Figure 9.

[66] See *Untersuchungen*, p. 99, *EW* 91. Note that, according to this figure, the waves at a certain distance are cylindrical instead of spherical. The experimental error was later detected by HERTZ on theoretical grounds (see *Untersuchungen*, p. 159, *EW* 148–149).

came from the revealed possibilities of playing with "waves in wires". After the negative results from 11th of November to the 22nd of December 1887, HERTZ obtained a positive proof of the propagation in time within the 23rd and 27th of December and confirmed it between the 28th and 30th of December. These experiments deal with the finite velocity at which the electrodynamic force propagates (in contrast with the electrostatic one) along an equatorial line, but the related paper N° 7_{Ak} (written up on 21 January 1888) does not mention any waves in space.

The third step leading to waves in space is hinted at by the same confirming experiments of the last days of December. HERTZ begins first to see along this equatorial line of propagation the "induction wave" or "air wave" (27 December, *Protokolle*), and the "induction waves in air" or "electrodynamic waves" (28 December, *Protokolle* and Diary respectively). Immediately he looks for the shape of these waves in the meridian plane or, as he says, "the spreading of the action throughout the whole classroom towards all sides" and, he obtains some stationary lines of the mean direction of the electric force (29 December, *Protokolle*; see 30 December, Diary). He will explain these lines in paper N° 5 as mainly electrostatic ones nearby, and electrodynamic ones at a distance. But the cyclic points in between, for which this mean direction is not defined, will be explained in a second drawing as "forces running around" (29 December, *Protokolle*). In HERTZ's imagination, the stationary lines become a live wave with a complicated periodic movement.

But even at this stage, the waves were mostly imaginary. HERTZ's experimental conviction came with his painful study of the stationary waves, carried out during March 1880 and published in paper N° 8, "On electrodynamic waves in the air and their reflection". The hint for this rational strengthening of the third step was also experimental: the unexpected effects of shadow and reflection on metal sheets and on the wall (29 December, Diary and *Protokolle*). The wave formation was studied by theory during April to October 1888 "according to Maxwell's theory" and published in paper N° 9, and the optical properties of an "electric ray" of short waves were studied experimentally in November to December 1888 and published in paper N° 11. These two papers gave to the scientific community electromagnetic waves as a confirmation of MAXWELL's theory. But, as HERTZ says at the end of paper N° 9, MAXWELL's theory can be electrodynamically reinterpreted "by introducing the ether as a dielectric in the manner indicated by von Helmholtz". Thus the final reason in favor of MAXWELL's theory is its simplicity, contrasted with the artificiality of HELMHOLTZ's limiting case which HERTZ calls HELMHOLTZ's "representation" ("Darstellung") of MAXWELL's "concept" ("Vorstellung").

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