Maxwell, Hertz, the Maxwellians, and the Early History of Electromagnetic Waves

***Dipak L. Sengupta*[1] *and Tapan K. Sarkar*[2]**

[1]Radiation Laboratory, Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI 48109-2122 USA
E-mail: sengupdl@eecs.umich.edu

[2]Department of Electrical Engineering and Computer Science
Syracuse University
Syracuse NY 13244-1240 USA
E-mail: tksarkar@mailbox.syr.edu

Abstract

In 1864, Maxwell conjectured from his famous equations that light is a transverse electromagnetic wave. Maxwell's conjecture does not imply that he believed that light could be generated electromagnetically. In fact, he was silent about electromagnetic waves, and their generation and detection. It took almost a quarter of a century before Hertz discovered electromagnetic waves and his brilliant experiments confirmed Maxwell's theory. Maxwell's ideas and equations were expanded, modified, and made understandable by the efforts of Hertz, FitzGerald, Lodge, and Heaviside, the last three being referred to as the "Maxwellians." The early history of electromagnetic waves, up to the death of Hertz in 1894, is briefly discussed. The work of Hertz and the Maxwellians is briefly reviewed in the context of electromagnetic waves. It is found that historical facts do not support the views proposed by some, in the past, that Hertz's epoch-making findings and contributions were "significantly influenced by the Maxwellians."

Keyword: History; light; electromagnetic fields; electromagnetic propagation; electromagnetic waves; Maxwell equations; Maxwell; Hertz; Maxwellians

1. Introduction

In the year 1864, James Clerk Maxwell (1831-1879) proposed his "Dynamical Theory of the Electromagnetic Field" [1], wherein he observed theoretically that an electromagnetic disturbance travels in free space with the velocity of light. He then conjectured that light is a transverse electromagnetic wave. Although the idea of electromagnetic waves was hidden in the set of equations proposed by Maxwell, he had, in fact, said virtually nothing about electromagnetic waves other than light, nor did he propose any idea for generating such waves electromagnetically. It has been stated [2, Chapter 2, p. 24] that "There is even some reason to think that he (Maxwell) regarded the electrical production of such waves as an impossibility." Heinrich Hertz (1857-1894) discovered electromagnetic waves around the year 1888 [3, Chapter 7, pp. 107-123]; the results of his epoch-making experiments and his related theoretical work confirmed Maxwell's prediction, and helped in the general acceptance of Maxwell's electromagnetic theory. However, it is not commonly appreciated that "Maxwell's theory that Hertz's brilliant experiments confirmed was not quite the same as the one Maxwell left at his death in the year 1879" [2, Chapter 2, p. 24]. It is interesting to note how the relevance of electromagnetic waves to Maxwell and his theory, prior to Hertz's experiments and findings, are described in [2, Chapter 2, pp. 29-30]: "Thus Maxwell missed what is now regarded as the most exciting implication of his theory, and one with enormous practical consequences. That relatively long electromagnetic waves or perhaps light itself, could be generated in the laboratory with ordinary electrical apparatus was unsuspected through most of the 1870's."

Maxwell's ideas and equations were expanded, modified, and made understandable after his death, mainly by the efforts of Heinrich Hertz, George Francis FitzGerald (1851-1901), Oliver Lodge (1851-1940) and Oliver Heaviside (1850-1925). The last three of these were christened as "The Maxwellians" by Heaviside [2, Chapter 2; 5].

The history of electromagnetic waves up to the year 1894 is briefly reviewed in this paper. A short discussion of Maxwell's original equations, and some brief comments on the work of Hertz and the Maxwellians, is given in the context of electromagnetic waves. It is found that historical facts do not support the views expressed by some in the past [4, p. 2] that Hertz's epoch-making findings and other contributions in electromagnetics were "significantly influenced by the Maxwellians."

2. Speculations of Electromagnetic Propagation Before Maxwell

There were natural philosophers and scientists before Maxwell who speculated [5] on the manner in which electric and magnetic influences or effects are transmitted through space. In 1855, the prince of mathematics, Karl Friedrich Gauss (1777-1855), considered the idea that electric actions propagate between the charges with finite velocity, but he resolved not to publish his research because he could not design a mechanism to achieve that transmission. More than one attempt to realize Gauss's aspiration was made by his pupil, Riemann. In 1853, Riemann proposed [5] to replace Poisson's equation for the electrostatic potential by a wave equation, according to which the changes in the potential due to changing electricity would propagate outward from the charges with the velocity of light. Although this is in agreement with the view that is now accepted as correct, Riemann's hypothesis was too trivial to serve as the basis of a complete theory.

It is now known [6] that in a deposition with the Royal Society (London), entitled "The Original Views," Michael Faraday (1791-1867) considered the idea that electric and magnetic effects "are progressive and require finite time for their transmission." Faraday did not find time to provide experimental evidence to support his views and, hence, wished the deposition, submitted in 1832, to remain unopened for at least 100 years. It should be noted that in his 1864 paper, Maxwell [1] commented on Faraday's thought in this regard in the following manner:

> The conception of the propagation of transverse magnetic disturbances to the exclusion of normal ones is distinctly set forth * [**Philosophical Magazine*, **III**, p. 447] in his "Thoughts on Ray Vibrations." The electromagnetic theory of light, as proposed by him, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation.

3. Maxwell's Electromagnetic Theory of Light

In his 1864 paper, read at the Royal Society (London), Maxwell introduced 20 equations involving 20 variables [1]. These equations together expressed mathematically virtually all that was then known about electricity and magnetism. Through these equations, Maxwell essentially summarized the work of Hans C. Oersted (1777-1851), Karl F. Gauss (1777-1855), Andre M. Ampere (1775-1836), Michael Faraday (1791-1867), and others, and added his own radical concept of "displacement current" to complete the theory.

To place Hertz's contributions in proper perspective in the context of Maxwell's proposed "Dynamical Theory of the Electromagnetic Field," and his conjecture therein regarding the nature of light [1] – and also for historical reasons – it is appropriate to review the original 20 equations introduced by Maxwell, and how he arrived at the crucial conjecture mentioned earlier. For this purpose, Maxwell's original variables and equations are recast under modern notation. Table 1 shows the names and symbols used by Maxwell for the variables, along with their identification by modern vector/scalar notation. Observe that the sets of three quantities appearing in each of the first six entries in column two of Table 1 respectively represent the three rectangular (x, y, z) components of the corresponding vector quantities given in column three.

Table 1. Twenty variables originally introduced by Maxwell ([1], p. 71).

Variable Name Used by Maxwell (Equivalent Modern Name)	Symbol Used by Maxwell	Modern Equivalent Vector/ Scalar
Electromagnetic Momentum (Magnetic Vector Potential)	F, G, H	$\vec{A}$
Magnetic Force (Magnetic Field Intensity)	α, β, γ	$\vec{H}$
Electromotive Force (Electric Field Intensity)	P, Q, R	$\vec{E}$
Current Due to True Conduction (Conduction Current Density)	p, q, r	$\vec{J}$
Electric Displacement (Electric Flux Density)	f, g, h	$\vec{D}$
Total Current Including Variation of Displacement (Conduction plus Displacement Current Density)	$\left\{ \begin{array}{l} p^1 = p + \frac{df}{dt} \\ q^1 = q + \frac{dg}{dt} \\ r^1 = r + \frac{dh}{dt} \end{array} \right\}$	$\vec{J}_T$
Quantity of Free Electricity (Volume Density of Electric Charge)	e	ρ
Electric Potential (Electric Scalar Potential)	ψ	ψ

Maxwell also indirectly used another variable (not shown in Table 1) named "the magnetic induction." Its three components in an isotropic medium are $\mu\alpha$, $\mu\beta$, and $\mu\gamma$, with μ being the "coefficient of magnetic induction." We now call this the magnetic flux density vector, $\vec{B} = \mu\vec{H}$, with μ being the permeability of the medium.

With the variables given in Table 1 and for an isotropic medium, Maxwell introduced 20 equations in component forms numbered (A)-(H), which formed the basis for his proposed "Dynamical Theory of the Electromagnetic Field" [1]. In our modified notation, these equations may be represented by the following:

$$\vec{J}_T = \vec{J} + \frac{\partial \vec{D}}{\partial t}, \tag{A}$$

$$\mu\vec{H} = \vec{B} = \nabla \times \vec{A}, \tag{B}$$

$$\nabla \times \vec{H} = 4\pi\vec{J}_T = 4\pi\left[\vec{J} + \frac{\partial \vec{D}}{\partial t}\right], \tag{C}$$

$$\vec{E} = \begin{array}{c} \mu\left(\vec{v} \times \vec{H}\right) \\ \text{or } \left(\vec{v} \times \vec{B}\right) \end{array} - \frac{\partial \vec{A}}{\partial t} - \nabla\psi, \tag{D}$$

[Note: Maxwell called Equation (D) the equation of electromotive force in a conductor moving with velocity $\vec{v}$ in an isotropic medium.]

$$\vec{E} = k\vec{D}, \tag{E}$$

where k is the "coefficient of electric elasticity" as it was called by Maxwell. [Note: Compare Equation (E) with the modern Equation, $\vec{D} = \varepsilon\vec{E}$, with ε being the permittivity of the medium.]

$$\vec{E} = \rho'\vec{J}, \tag{F}$$

with ρ' being the "specific resistance" or resistivity of the material. [Note: (1.) Maxwell used the symbol ρ instead ρ'. We are using ρ' so as not to conflict with our notation ρ for volume charge density. (2.) Compare Equation (F) with the modern equation, $\vec{J} = \sigma\vec{E}$, with $\sigma = 1/\rho'$.]

$$\nabla \bullet \vec{D} = \rho, \tag{G}$$

$$\nabla \bullet \vec{J} + \frac{\partial\rho}{\partial t} = 0. \tag{H}$$

It is clear that there are 20 equations in Equations (A)-(H). It should be noted that Maxwell used the Gaussian system of units, in which the electric and magnetic quantities are expressed in cgs electrostatic and cgs electromagnetic units, respectively (i.e., esu and emu, respectively). The appearance of the factor 4π in Equation (C) is due to the use of this unit. It is important to retain the original units used by Maxwell: they are essential for appreciating how Maxwell arrived at his famous conjecture.

The use of the parameter k in Equation (E) needs some explanation. From the considerations of mechanical forces experienced by electric and magnetic charges, and the relationship between esu and emu, Maxwell showed that ([1], p. 569)

$$k = 4\pi\frac{C^2}{K}, \tag{1}$$

where K is the "inductive or specific inductive capacity" (or the dielectric constant) of the medium,

and

$$C = \frac{\textit{one emu of electric charge}}{\textit{one esu of electric charge}}.$$

In Gaussian units, for air (free space), $\mu = 1$ and $K = 1$.

Maxwell assigned strong physical significance to the vector and scalar potentials, $\vec{A}$ and ψ, both of which played dominant roles in his formulation. He also assumed a hypothetical mechanical medium to justify the existence of displacement current in free space: this assumption produced strong opposition to Maxwell's theory from many scientists of his time. It is well known now that Maxwell's equations, as we know them now, do not contain any potential variable; neither does his electromagnetic theory require any assumption of an artificial medium (as shown by Hertz and Heaviside) to sustain his "displacement current" in free space. The original interpretation given to the "displacement current" by Maxwell is no longer used; however, we still retain the term in honor of Maxwell. Although modern Maxwell's equations appear in a modified form, the equations originally introduced by Maxwell in 1864 formed the foundation of electromagnetic theory, which, together, may very well be referred to as Maxwell's electromagnetic theory.

Maxwell now assumed that a plane wave is propagating through the field, with velocity V in a direction given by the unit vector $\hat{w}$, the direction cosines of which in the x, y, z directions are l, m, n, respectively. Then, all electromagnetic functions will be functions of

$$w = lx + my + nz - Vt. \tag{2}$$

By using the magnetic-force equation (B), Maxwell showed that

$$\mu\vec{H} \bullet \hat{w} = 0, \tag{3}$$

i.e., $\mu\vec{H} \perp \hat{w}$, which implied that the "direction of magnetization" must be in the plane of the wave (i.e., in the wavefront). Assuming an insulating and stationary isotropic medium $(\vec{J} \equiv 0,\ \vec{v} \equiv 0)$, he obtained the following from Equations (B), (C), and (D):

$$k[\nabla(\nabla \bullet \vec{A}) - \nabla^2\vec{A}] = -4\pi\mu\left[\frac{\partial^2\vec{A}}{\partial t^2} + \nabla\left(\frac{\partial\psi}{\partial t}\right)\right], \tag{4}$$

where $\nabla = \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} + \hat{z}\frac{\partial}{\partial z}$.

The three rectangular components of Equation (4) are the same as those given by Maxwell as Equation (68) in [1, p. 578]. Maxwell then eliminated $\vec{A}$ and ψ from each of the three equations in Equation (4), and obtained three similar equations for the three rectangular components of $\vec{H}$. Since this is not obvious, we shall briefly outline the procedures involved. After taking the difference of the y and z derivatives of the z and y components, respectively, of Equation (4), and making use of Equation (B), it can be shown that the x component of $\vec{H}$ satisfies the following equation:

$$k\nabla^2\mu H_x - 4\pi\mu\frac{\partial^2\mu H_x}{\partial t^2} = 0. \tag{5}$$

Equations similar to Equation (5) were obtained for H_y and H_z, and the three equations were shown as a set of equations numbered Equation (69) in [1, p. 579].

Assuming that H_x, H_y, H_z are functions of w (given by Equation (2)), it can be shown that Equation (5) yields

$$k\mu\frac{d^2H_x}{dw^2} = 4\pi\mu^2V^2\frac{2d^2H_x}{dw^2}, \tag{6}$$

which implies that

$$V = \pm\sqrt{\frac{k}{4\pi\mu}}. \tag{7}$$

Similarly, the other equations for H_y, H_z yield the same value of V, so that the wave propagates in either direction $\pm\hat{w}$ with velocity V.

At this stage, we quote Maxwell [1, p. 579]:

> This wave consists entirely of magnetic disturbances, the direction of magnetization being in the

> plane of the wave. No magnetic disturbance whose direction of magnetization is not in the plane of the wave can be propagated as a plane wave at all.
>
> Hence magnetic disturbances propagated through the electromagnetic field agree with light in this, that the disturbance at any point is transverse to the direction of propagation, and such waves may have all the properties of polarized light.

Although Maxwell considered only a magnetic disturbance in [1], he later [7] showed that $\vec{E} \perp \hat{w}$ (i.e., $\vec{E} \bullet \hat{w} = 0$), and also that $\vec{E} \perp \vec{H}$. Thus, both the electric and magnetic disturbances lie in the plane of the wave, they are mutually orthogonal, and together they propagate as a plane electromagnetic wave. We quote Maxwell again [7]: "The mathematical form of the disturbance therefore agrees with that of the disturbance which constitutes light, being transverse in the direction of propagation."

With k given by Equation (1), Equation (7) yields

$$V = \frac{C}{\sqrt{K\mu}}. \tag{8}$$

Maxwell considered air (free space), for which $K = 1$ and $\mu = 1$ (in Gaussian units); thus

$$V = C = \frac{\textit{one unit of electric charge in emu}}{\textit{one unit of electric charge in esu}}.$$

Purely electromagnetic measurements [8] yielded $C = 314{,}740{,}000$ m/s = c = velocity of light in free space.

Maxwell then made his most significant conjecture [1, p. 580]: "The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

Thus, the most important consequence of Maxwell's proposed equations was to establish the possibility of an electromagnetic wave propagating with a velocity that could be calculated from the results of purely electrical measurements. Indeed, as mentioned earlier, electromagnetic measurements [8] indicated that the velocity equaled that of light in free space. This led Maxwell to his famous conjecture that light is a transverse electromagnetic wave, a conjecture later verified by Hertz. However, it is important to note that Maxwell did not make any comment about the generation of light waves and/or electromagnetic waves of lower frequencies by electromagnetic means. There is no indication left behind by him that he believed such was even possible. Maxwell did not live to see his prediction confirmed experimentally and his electromagnetic theory fully accepted. The former was confirmed by Hertz's brilliant experiments. Maxwell's theory received universal acceptance, and his original equations – in a modified form – became the language of electromagnetic waves and electromagnetics, mainly due to the efforts of Hertz and Heaviside.

4. Acceptance of Maxwell's Theory

How the investigations of Hertz and the Maxwellians, during the years 1879 (the year Maxwell died) to 1894 (the year Hertz died), finally led to the acceptance of Maxwell's theory by the scientific community is well documented. The contributions of the Maxwellians were described in [2, 4], and those of Heaviside in [2, 9]. Hertz's original contributions can be found in [3, 10-11]; descriptions of Hertz's experimental arrangement were given in [12, 13], and of Hertz's biography and work in [14]. Since this has been discussed in detail in the literature, in the following we give only short comments on some appropriate items in the context of the topic of our interest.

4.1 Maxwell's Equations

Maxwell's original equations were modified and later expressed in the form we now know as "Maxwell's Equations" independently by Hertz and Heaviside. Their work discarded the requirement of a medium for the existence of the "displacement current" in free space, and they also eliminated the vector and scalar potentials from the fundamental equations. Thus, Hertz and Heaviside, independently, expressed Maxwell's equations involving only the four field vectors, $\vec{E}$, $\vec{B}$, $\vec{D}$, and $\vec{H}$. Although priority is given to Heaviside for the vector form of Maxwell's equations, it is important to note that Hertz's 1884 paper [15] provided the rectangular form of Maxwell's equations, which also appeared in his later paper of 1890 [16]. It is to be noted that the coordinate forms of the equations given in [15] were first obtained by Hertz.

It is appropriate to mention here that the importance of Hertz's theoretical work [15] and its significance appear not to have been fully recognized [17]. In his paper, Hertz started from the older action-at-a distance theories of electromagnetism and proceeded to obtain Maxwell's equations in an alternate way, which avoided both the mechanical models Maxwell had originally used and his formulation of displacement current. In fact, this paper formed the basis for all of Hertz's future theoretical and experimental contributions to electromagnetism. D'Agostino [18] was the first to point out the importance of this paper in the development of Hertz's ideas. New insights into Hertz's theory of electromagnetism were discussed in [17], where the entire work was recast in modern notation for ease of understanding. The authors of [17] then concluded, "It is remarkable that an alternate method was available to derive Maxwell's equations based on quite a different approach." The physical insight of Hertz's work seems not to have been well appreciated in the past. The contents of Hertz's theory probably had a great impact years later on his design of experiments. D'Agostino points out [18] that in his 1884 paper, Hertz developed a theory of free propagation of electromagnetic forces that was inspired by purely electromagnetic – not optical – phenomena. The fundamental contribution of Hertz's development was a theory of the source-field relation, unknown to Maxwell.

In contrast to the 1884 paper, in his 1890 paper [16], Hertz postulated Maxwell's equations, rather than deriving them in an alternative form. The equations written in component forms, rather than in vector form as done by Heaviside [9], brought unparalleled clarity to Maxwell's theory. After reading this 1890 paper by Hertz, Arnold Sommerfeld had this to say: "It was as though scales fell from my eyes when I read Hertz's great paper" [19]. The paper, entitled "On the Fundamental Equations of Electrodynamics for Bodies at Rest," served as a model for Sommerfeld's lectures on electrodynamics since his student days [19, p. 4].

4.2 Electromagnetic Waves

A few months before the death of Maxwell, Lodge began to look into the possibility of producing electromagnetic waves [2, p.

30]. He recorded several ideas in his laboratory notebook regarding the possibility of generating light electromagnetically. The first unambiguous description of how to generate electromagnetic waves other than light were given by FitzGerald and Lodge between 1879 and 1883 [2, p. 24]; however, they did not have any idea how to detect them. Thus, although the Maxwellians utilized Maxwell's theory to show the possibility of generating electromagnetic waves, they grappled with the idea of actually producing and detecting such waves in practice without any success. This was to be accomplished by Hertz.

Maxwell's predictions and theory were confirmed by a set of brilliant experiments, conceived and performed by Hertz, who generated, radiated (transmitted), and received (detected) electromagnetic waves of frequencies lower than light. His initial experiment started in 1887, and the decisive paper on the finite velocity of electromagnetic waves in air was published in 1888 [3, Chapter 7, pp. 107-123]. The English translation of Hertz's original publications [15] on experimental and theoretical investigation of electric waves is still a decisive source of the history of electromagnetic waves and Maxwell's theory. A description of Hertz's experimental setup and his epoch-making findings are given in [12].

It is important to note that Hertz and the Maxwellians were not aware of each other's work until Hertz published his 1888 work. The Maxwellians appreciated Hertz's brilliant work and its implications. By early 1889, FitzGerald and his assistant, Trouton, repeated most of Hertz's main experiments [2, p. 161; 4, p. 16]. Lodge and his group in Liverpool repeated Hertz's results in 1890 [4, p. 16]. "The Maxwellians quickly gave Hertz's experiments the widest possible publicity and labeled them from the first as a decisive new confirmation of Maxwell's theory" [2, p. 158]. FitzGerald was instrumental in awarding Hertz the Rumford Medal of the Royal Society.

After the 1888 results, Hertz continued his work at higher frequencies, and his later papers conclusively proved the optical properties (reflection, polarization, etc.) of electromagnetic waves, and thereby provided unimpeachable confirmation of Maxwell's theory and predictions.

It is appropriate to mention here that there were other people who, before Hertz, observed electromagnetic waves; however, they could not relate their observations to Maxwell's theory. Susskind [14, pp. 110-112] described that during 1875-1882, Thomas Alva Edison, Elihu Thompson, Amos Dolbear, and David Edwards Hughes observed some form of electromagnetic waves. However, none of them was well versed in Maxwell's theory or electromagnetics. They could not correlate such observations with electromagnetic waves, and thereby missed the deep significance of their observations. Hughes [6, pp. 28-30] did detect the standing waves, with nodes and antinodes at fixed distances, produced by interference between incident and reflected waves, but he did not realize that until much later. Hertz, a trained physicist and a believer in Maxwell's theory, observed electromagnetic waves and related his findings to Maxwell's theory, and thereby became the discoverer of electromagnetic waves.

5. Hertz and the Maxwellians

The Maxwellians, a book by Hunt [2, pp. 38-39 and pp. 181-182], described the investigations of FitzGerald, Lodge, and Heaviside historically and chronologically, and of Hertz, which helped to insure the final acceptance of Maxwell's theory and predictions by the scientific community. Another book, entitled *Hertz and the Maxwellians*, by O'Hara and Pritcha [4], discussed selected works of Hertz. It documented, for the first time in one place, the correspondence between Hertz and the Maxwellians, and provided English translations of the correspondence. In addition, it contains much valuable information about Hertz's personal life. O'Hara and Pritcha began their book with the following statements [4, pp. 1-2]:

> ...whereas the beginning of Hertz's career coincided with the death of Maxwell and no direct contact between them would have been possible, and association, mainly in the form of correspondence, between Hertz and the disciples of Maxwell in Britain and Ireland did come about and had a significant influence on his thought and researches. One of the aims of this study is to illuminate their association and to consider the extent of its influence of Hertz's work....
>
> It will be argued that Hertz's conversion to Maxwell's theory was a gradual process which was influenced by his association with the "Maxwellians:" his experimental work too was to benefit from these contacts.

On the basis of our study, it is argued that the basic premise of the book [4] quoted above is flawed. Since the first letter appearing in [4] is dated 1888, after the publication of Hertz's seminal paper [3, Chapter 7, pp. 107-123], and since there is no evidence that there was any contact between Hertz and the Maxwellians before 1888, it is not possible "that the Maxwellians significantly influence Hertz's researches in electromagnetics." Due to the late date at which correspondence started between Hertz and the Maxwellians, the most that they could have influenced his work is represented by the last two papers on electromagnetics, included in the collected works, *Electric Waves* [15].

It is appropriate here to quote Hertz's own words to comment on this [3, pp. 1-3]:

> I may be permitted to record the good work done by two English colleagues who at the same time as myself were striving towards the same end. In the same year in which I carried out the above research, Professor Oliver Lodge in Liverpool investigated the theory of the lightning inductor and in connection with this carried out a series of experiments on the discharge of conductors which led him on the observations of oscillations and waves in wires. In as much as he entirely accepted Maxwell's views, and eagerly strove to verify them, there can scarcely be any doubt that if I had not anticipated him he would also have succeeded in observing waves in air, and had some years before endeavored to predict with the aid of theory the possibility of such waves, and to discover the conditions for producing them. My own experiments were not influenced by the researches of these physicists, for I only knew them subsequently. Nor indeed do I believe that it would have been possible to arrive at a knowledge of these phenomena by the aid of theory alone. For their appearance upon the scene of our experiments depends not only upon their theoretical possibility, but also upon a special and surprising property of the electric spark which could not be foreseen by any theory".

There is no evidence of interaction of any kind between Hertz and the Maxwellians during or before the preparation of Hertz's 1884 paper [15] on the modified form of Maxwell's equations. It is interesting to note that in his 1890 paper on Maxwell's equations [16], Hertz made the following comments [9, pp. 196-197] on Heaviside's work on the similar topic:

> Again the incompleteness of form referred to renders it more difficult to apply Maxwell's theory to special cases. In connection with such appreciation I have been led to endeavor for some time past to sift Maxwell's formulae and separate their essential significance from the particular form in which they first happened to appear. The results at which I have arrived are set forth in the present paper. Mr. Oliver Heaviside has been working in the same direction ever since 1885. From Maxwell's equations he moves the same symbols as myself; and the simplest form which these equations (These equations will be found in the Phil. Mag. for February 1888. Reference is there made to earlier papers in The Electrician for 1885, but this source was not accessible to me) thereby attain is essentially the same as that at which I arrive. In this respect, then, Mr. Heaviside has the priority.

The four equations in vector notation, containing the four electromagnetic field vectors, are now commonly known as Maxwell's equations. However, Einstein and Heaviside referred to them as the Maxwell-Hertz and Maxwell-Heaviside and Hertz equations, respectively [2, p. 182].

As described in [4], contact between Hertz and the Maxwellians started and deepened after Hertz's 1888 paper was published. It is possible that contact with Heaviside may very well have modified Hertz's 1890 paper. However, his 1884 paper, wherein Hertz introduced the coordinate form of the modified Maxwell's equations, was worked out before the above-mentioned contact with Heaviside.

It is beyond any doubt that Maxwell's original theory and thinking had profound influence on Hertz. But Hertz's epoch-making discovery of electromagnetic waves, his research into electromagnetics, and the manner in which he formulated Maxwell's equations – in fact, the research by which Hertz validated and confirmed Maxwell's theory and predictions – were certainly not significantly influenced by the Maxwellians, as implied in [4].

6. Conclusion

Maxwell's original equations, forming the foundation of electromagnetic theory, and his famous conjecture regarding light as an electromagnetic wave, have been briefly discussed in the context of electromagnetic waves in general. The early history of electromagnetic waves and the part played by Hertz and the Maxwellians (i.e., FitzGerald, Lodge, and Heaviside) towards the confirmation and acceptance of Maxwell's theory have been presented. It was found that the Maxwellians had minimal or no influence on Hertz's discovery of electromagnetic waves and on his other accomplishments in electromagnetics.

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Dipak L. Sengupta received the BSc (Hons) degree in Physics and the MSc degree in Radiophysics from Calcutta University, Calcutta, India, in 1950 and 1952, respectively, and the PhD degree in Electrical Engineering from the University of Toronto, Ontario, Canada, in 1958. In 1959, he was a Research Fellow in electronics at Harvard University, Cambridge, MA. During 1963-64, he was an Assistant Professor in Electrical Engineering, University of Toronto. From 1964 to 1965, he was an Assistant Director for the Central Electronics Engineering Research Institute, Pilani, India. During 1959-1963 and 1965-1986, he was with the University of Michigan, Ann Arbor (as a Professor and Research Scientist), conducting research at the Radiation Laboratory and teaching in the Electrical Engineering and Computer Science Department. In 1986, he joined the University of Detroit Mercy, and was a Professor and Chairman of the Department of Electrical Engineering and Physics until 1996. Afterwards, he continued as a Professor from 1996 to 2001, when he retired. He was made Professor Emeritus there in 2002. Since 1988, he has also been with the Radiation Laboratory at the University of Michigan, Ann Arbor, as a Research Scientist.

During 1992-93, he was a Fulbright Visiting Lecturer in India. In 1996, he was a Visiting Professor at the Instituto Technologico y de Estudio Superiores de Monterrey, Monterrey, Mexico. His professional interests include the areas of antennas, electromagnetics, electromagnetic compatibility, and navigation systems. Currently, he is interested in the historical aspects of electromagnetics and antennas.

Prof. Sengupta is a Life Fellow of the IEEE. He is a member of Commission B of the US National Committee of the International Union of Radio Science (URSI), Sigma Xi, and Eta Kappa Nu. He is listed in *American Men and Women of Science, Who's Who in America, Who's Who in Technology Today, Who's Who in Electromagnetics,* and *Dictionary of International Biography.* From 1976 to 1978, he served as Vice Chair and then Chair of the Southeast Michigan Section of the IEEE Antennas and Propagation, Microwave Theory and Techniques, and Electron Devices Societies. During 1976-1978, he was Secretary of USNC/URSI Commission B. During 1981-1985, he was an Associate Editor of the *IEEE Transactions on Antennas and Propagation.* In 1969, he received the IEEE Certificate of Achievement for the outstanding contribution to the *IEEE Transactions on Antennas and Propagation.* He is also the recipient of a number of IEEE Certificates of Recognition for Outstanding Services.

Tapan K. Sarkar received the BTech degree from the Indian Institute of Technology, Kharagpur, India, in 1969, the MScE degree from the University of New Brunswick, Fredericton, Canada, in 1971, and the MS and PhD degrees from Syracuse University, Syracuse, New York, in 1975.

From 1975 to 1976, he was with the TACO Division of the General Instruments Corporation. He was with the Rochester Institute of Technology, Rochester, NY, from 1976 to 1985. He was a Research Fellow at the Gordon McKay Laboratory, Harvard University, Cambridge, MA, from 1977 to 1978. He is now a Professor in the Department of Electrical and Computer Engineering, Syracuse University; Syracuse, NY. His current research interests deal with numerical solutions of operator equations arising in electromagnetics and signal processing with application to system design. He obtained one of the "best solution" awards in May, 1977, at the Rome Air Development Center (RADC) Spectral Estimation Workshop. He has authored or co-authored more than 250 journal articles and numerous conference papers, and has written chapters in 28 books. He has authored ten books, including the latest ones, *Iterative and Self Adaptive Finite-Elements in Electromagnetic Modeling* (1998) and *Application of Wavelets in Electromagnetic and Signal Analysis* (2002), both published by Artech House.

Dr. Sarkar is a Registered Professional Engineer in the State of New York. He received the Best Paper Award of the *IEEE Transactions on Electromagnetic Compatibility* in 1979 and at the 1997 National Radar Conference. He received the College of Engineering Research Award in 1996, and the Chancellor's Citation for Excellence in Research in 1998 at Syracuse University. He was an Associate Editor for Feature Articles of the *IEEE Antennas and Propagation Society Newsletter,* and he was the Technical Program Chair for the 1988 IEEE Antennas and Propagation Society International Symposium and URSI National Radio Science Meeting. He was the Syracuse Chapter Chair for the Antennas and Propagation and Microwave Theory and Techniques Societies from 1996-2002. He is a Distinguished Lecturer for the Antennas and Propagation Society. He is on the editorial board of the *Journal of Electromagnetic Waves and Applications* and of *Microwave and Optical Technology Letters.* He has been appointed a USNC delegate to many URSI General Assemblies. He was the Chair of the Inter-Commission Working Group on Time Domain Metrology of URSI (1990-1996). He is a Fellow of the IEEE. Dr. Sarkar is a member of Sigma Xi and USNC/URSI Commissions A and B. He received the title Docteur Honoris Causa from Universite Blaise Pascal, Clermont Ferrand, France, in 1998, and the Friend of the City (Clermont Ferrand) in 2000.