HERTZ AND MICHELSON

Irwin I. Shapiro
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA, USA

1. INTRODUCTION

I have mixed feelings about giving the opening talk at this symposium. On the one hand I am delighted to welcome you to this conference on the impact of VLBI on astrophysics and geophysics. On the other hand I am very sad that Ed Purcell is bothered by a bad back and cannot give the introduction as originally scheduled. Ed is one of the truly great of the world's physicists and one of the nicest persons ever born. My substituting for Ed is somewhat like Bill Buckner pinch hitting for Lou Gehrig. (Those who do not understand this reference to American baseball might have a better appreciation after viewing tonight's Red Sox game.)

We originally intended this symposium to be a celebration of the 20th anniversary of the first successful VLBI experiments. However, while beginning to plan for this event, I realized that 1987 would be the 100th anniversary of the discovery of radio waves by Heinrich Hertz. A few days ago it occurred to me that 1987 was also the 100th anniversary of the Michelson-Morley experiment. These developments together, of course, supply the two ingredients of VLBI -- radio waves and interferometry. Hence, it seemed appropriate to dedicate the conference to both Heinrich Hertz and Albert Michelson. I wanted to invite both, but I was a little late getting out the invitations.

To honor these two gentlemen in absentia I will go over a few -- very few -- of the highlights of their discoveries and of their lives.

2. HERTZ

Like our George Washington, Hertz (Fig. 1) was born on 22 February, a child prodigy who changed from a career in engineering to one in physics, just as did Purcell. Like Mozart, but unlike Purcell, Hertz died very young, of a bone malignancy in his head -- a terrible tragedy for his family and for science.

In the 1870s and 1880s a major question in physics concerned electrodynamics. Maxwell's theory was not yet well accepted. In England, yes; on the continent, hardly at all. Competing on the continent were the so-called action-at-a-distance theories of Newmann and Weber. Experimental distinctions were not easy to come by.

M. J. Reid and J. M. Moran (eds.), The Impact of VLBI on Astrophysics and Geophysics, 1–6.

The conflict concerned primarily the consequences of open circuits which Maxwell resolved with his ingenious fourth equation that modified Ampere's law by introducing the displacement current and thereby insuring conservation of charge. One question concerned the possible generation in space of electric waves, predicted by Maxwell's theory, but not by the others. While at the Technische Hochschule in Karlsruhe, Hertz devised a method[1] to attempt to detect such electric waves ("radio waves" to us). He used for his primary (transmitter) circuit an induction-coil, spark-gap dipole arrangement which, as Purcell deduced, radiated ~10 watts at ~60 MHz. The oscillations were set up in this spark gap by means of "the most powerful discharges that could be obtained from a large induction coil." His secondary (receiver) circuit was a circle of wire 35 cm in radius with a dielectric "handle" and a short spark gap, adjustable with a micrometer screw for ease in rotating it and in placing it at any desired position. For some experiments, Hertz modified the secondary to be very nearly in resonance with the primary through soldering small pieces of sheet metal to the poles to change the capacitance so as to maximize the spark length in a given position and orientation. By inducing repeated discharges and measuring the effects at many different places around the room with his receiver, Hertz was able to establish the presence of standing waves and to measure their length. Calculating frequency (see above) from the inductance and capacitance of the relevant components in the transmitter, much as physics undergraduate students would now do, Hertz then deduced the velocity of the radiation, a quite respectable 320,000 (+ 50% - 30%) km s^{-1}. At the end, Hertz noted how it was "certainly remarkable that proof of the finite rate of propagation should have been first brought forward in the case of a force which diminishes in inverse proportion to the distance, and not the square of the distance."

Fig. 1 Heinrich Hertz (1857-1894), in his prime, circa 1887.

To investigate these waves further, Hertz needed higher frequency radiation to make use of concave parabolic mirrors, while avoiding having his experiments distorted by the "disproportion between the length (~5 m) of the waves (previously) used and the dimensions which (he) was able .... to give to the mirror." By pushing the then state of the art to its limit, Hertz decreased the wavelength of the radiation to ~30 cm, a value, in fact, not too far from that used by the Canadian group in their first VLBI experiment in 1967. Hertz then constructed two identical zinc, concave, cylindrical, 12.5-cm focal length, paraboloids, forming them on a wooden template. The spark gap from the primary was placed on the focal line of one of the mirrors and the secondary gap was placed, in effect, on the focal line of the other, although the wires were arranged so that the spark gap was behind the mirror and could be adjusted and examined "without obstructing the course of the waves." In some cases, Hertz dealt with minute sparks -- only a few hundredths of a millimeter in length.

By placing "blocking" conductors at various places, Hertz established beyond a shadow of a doubt that the propagation was rectilinear; he also noted the lack of a sharp geometric shadow to the rays and the correspondence to diffraction, although he could not discern maxima and minima at the edges of the shadows. To demonstrate reflection, Hertz used 2m x 2m plain vertical "walls" of zinc, positioned in various ways with respect to the two mirrors. He determined the position of the wavefront with respect to the rays before and after reflection, in addition to the plane of oscillation before and after, all as a function of the angle of incidence. He, of course, established the equality of the angle of incidence and reflection, and noted that the reflection was more nearly "regular" than diffuse. He even placed his transmitter and receiver in adjoining rooms, with the reflector situated in the doorway between, to study large angles of incidence.

To investigate refraction Hertz made a large prism in the shape of an isosceles triangle, 1.2 m on a side, with about a 30° refracting angle. He made this prism from hard pitch, cast in wooden boxes, and blocked passage of any rays not going through the prism with conducting screens. For the refractive index, he obtained 1.7; for light, it was known to be between 1.5 and 1.6; the difference was within Hertz's (uncertain) estimate of the uncertainty.

Hertz also demonstrated that the electric waves were transverse and plane polarized. In particular, he rotated the "receiving" mirror until its focal line was perpendicular to that of the transmitter, and watched the sparks in the receiver gradually become more feeble and then disappear for the right-angle configuration. He further demonstrated polarization properties by interposing a screen of parallel copper wires; for example, with the wires making a 45° angle with the mutually perpendicular focal lines of the two mirrors, he was again able to observe sparks in the secondary and noted the analogy to "the brightening of the dark field of two crossed Nicols by the interposition of a crystalline plate in a suitable position." Hertz also established to his satisfaction that electric and magnetic oscillations in the wavefront were perpendicular to each other.

For Hertz, these experiments, in toto, removed any doubt about electric waves being the same as light waves, save for having far longer wavelengths. This grand synthesis of electromagnetic and light phenomena was of profound importance for physics.

Hertz's extraordinary thoroughness was perhaps nowhere better illustrated than in his discovery of the photoelectric effect. In his experiments on electric waves, he at times enclosed the (secondary) spark coil in a dark case to observe more easily the induced spark. The dielectric case he chose was, of course, transparent to electric waves. To Hertz's surprise, "the maximum spark-length became decidedly smaller inside the case" than when the coil was exposed directly to the primary. Removing the case in parts, he deduced that only the portion interposed between the secondary and the primary produced the effect. He continued with a painstakingingly thorough,

https://doi.org/10.1017/S0074180900133777 Published online by Cambridge University Press

exhaustive investigation of all conceivably relevant variables that might influence the effect; he deduced, for example, that its cause must travel in straight lines. By studying various interposed materials -- solid, liquid, and gaseous -- he found which ones did, and which did not, hinder this travel, and how the effects depended on the thickness of the interposed material. He even demonstrated that the effect could be produced with reflectors and refractors appropriately placed between the primary and the appropriately shielded secondary. After nearly 20 different sets of experiments, he concluded that ultraviolet light was the cause of this increase in the spark length.

Hertz was also no slouch as a theorist and, near the end of his life, while ill, concentrated on theory. He developed the modern form of Maxwell's equations, if not the vector and tensor notations. Maxwell's original formulation was rather abstruse from our point of view, being entangled with the then pervasive mechanical model of the world. Hertz stripped away the irrelevancies, including the attempted rationalizations in terms of the mechanical view, and gave those equations nearly the form we see on "T" shirts. His philosophy was also very modern; to the question "what is Maxwell's theory?," he responded that he knew no shorter or more definitive answer than "Maxwell's theory is Maxwell's set of equations."

Purcell, as a young graduate student, had gone to the Technische Hochschule in Karlsruhe and was in the very room in which Hertz's first experiments on radio waves were performed; he recalls clearly the inscription on the plaque there commemorating Hertz's achievements. Curiously, Purcell, who was trained in electrical engineering as an undergraduate, had not even seen Maxwell's equations, *per se*, when he went to Karlsruhe, and the "facts" of the fourth equation were then unknown to him. Needless to say, that condition neither lasted much longer nor hindered his later enormous contributions to physics.

3. MICHELSON

Now let me turn to Albert Michelson (Fig. 2). The Polish-born son of immigrants to the US[2], Michelson started his career at the Naval Academy in Annapolis, but was soon drawn to physics and, especially, optics. He was asked, at 25, to begin teaching an advanced physics course with a demonstration of the measurement of the speed of light by Foucault's rotating mirror method. Within a short time he saw how to improve this method significantly and, within about a year, had built the needed equipment and obtained a result: 299,940 km s^{-1} -- the first of his many improvements on the measurement of that fundamental quantity. His work brought him to the attention of the already renowned Simon Newcomb, and Michelson's scientific career was set by a transfer to the Nautical Almanac Office from the Naval Academy.

Maxwell, shortly before his death in 1879, wrote to David Todd, the then director of the Nautical Almanac Office, asking about the possibility of a celestial measurement of the aether drift. Maxwell was not sanguine, however, about the prospects for measuring any quantity proportional to "the square of the ratio of the earth's

https://doi.org/10.1017/S0074180900133777 Published online by Cambridge University Press

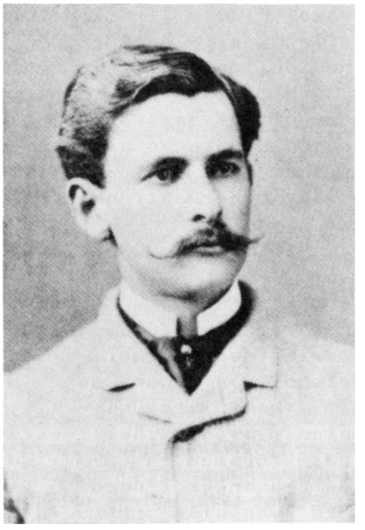

Fig. 2 Albert A. Michelson (1852-1931), in 1887, at the time of THE experiment.

velocity to that of light." Michelson, intrigued, took up the challenge; first he felt he needed advanced training in physics and so went to the University of Berlin. He developed his first interferometer in Europe, inspired by Fizeau's (1859) experiments, and performed his first aether drift experiment in 1881 in Germany. He was reportedly disappointed at the null result. In his report on this experiment, however, he had made a small, but embarrassing, mistake in calculation, immediately recognized and corrected independently by André Potier and by Hendrik Lorentz. This error -- the neglect of the effect of the earth's motion on the interferometer arm perpendicular to that of the motion -- did not affect, qualitatively, the null result, but did cast a bit of a cloud over its "credibility." Michelson's null result was apparently not taken very seriously in the physics community. Nonetheless, he wished to pursue and to improve his experiment. Even then, such undertakings required raising funds. Luckily, Michelson was quite adept at such endeavors. He had secured funds for his first experiment, with Newcomb's help, from Alexander Graham Bell's Volta Foundation; for his later experiment, he received an endorsement from Lord Rayleigh for a repetition of the experiment and recognized immediately its value, and used it, in raising the needed funds. The experiment, undertaken with Edward Morley, was carried out while Michelson was at the Case School of Applied Science (now part of Case-Western Reserve). The result, announced in 1887, almost exactly 100 years ago today, was now taken quite seriously by the world's scientists; it showed that any drift of the earth through the aether, if it existed, was less than 1/6 the earth's orbital velocity. Thus did interferometry first make its lasting mark.

Not long thereafter, c. 1890, Michelson tried to apply his technique to observations of the Galilean satellites of Jupiter. At that time there was also a mini-controversy raging over inconsistencies between different determinations of the sizes of these satellites. Michelson wrote a low-key letter to one of my professional ancestors here at the Harvard College Observatory, requesting permission to use the Great Refractor (15" diameter) to try out these interferometric measurements. After much procrastination for reasons lost in the mist of history, E. C. Pickering gave Michelson his chance. However, apparently a combination of delays, instrument problems, and bad seeing caused the endeavor to fail. It is not clear which was the most important cause. Michelson later succeeded in these measurements, in better seeing, at the Lick Observatory in California. As we all know, he went on early in this century to make important interferometric determinations, with Francis

Pease, of stellar diameters, using primarily the 100" diameter reflecting telescope on Mt. Wilson, the site of current advances in the application of optical interferometry to astrometry.

Michelson was respected throughout the physics and astronomy communities as a superb experimentalist. It was widely felt that only he could make an astronomical interferometer work and, perhaps because of that mystique, such interferometers were neither developed nor used by any other astronomers for many years.

4. HISTORICAL CONNECTIONS BETWEEN HERTZ AND MICHELSON

Hertz and Michelson both worked under Herman von Helmholtz in Berlin in the early 1880s. Although I found no definitive reference to their knowing one another, it could hardly have been otherwise: Von Helmholtz's group was rather small.

When Clark University in Worcester, MA was founded with the intent to have the finest obtainable faculty in science, both Hertz and Michelson were invited to join. Michelson went; Hertz did not. The reason proffered for Hertz's declination of the invitation, it is said, was his then recent marriage.

Both Hertz and Michelson measured the speed of light, although at vastly different wavelengths and with vastly different accuracy. Both were also connected with Albert Einstein's "wunder yahr" of 1905: Hertz through his discovery of the photoelectric effect and the establishment of the equivalence between radio and light waves, and Michelson (more tenuously) through the tight experimental limit he placed on any motion of the earth through the aether.

Hertz and Michelson both won the Rumford Prize of the Royal Society, albeit not in the same year. Michelson went on to win the Nobel Prize; Hertz doubtless would have won this prize, too, had he not died before its establishment. Michelson's Nobel citation did not even mention the aether-drift experiments; it emphasized his interferometer-based experiments directed toward the use of a wavelength of light as a universal standard of length. Hertz would most likely have been cited for his experiments on electric waves.

The first successful VLBI observations were also recognized by the Rumford Award of the American Academy of Arts and Sciences in 1971. The prize was split 21 ways, and many of the recipients are here today to help honor the 20th anniversary of this achievement.

The VLBI community has now proliferated from the original 21 to casts of hundreds, if not thousands. With all of you, I look forward to hearing about the fascinating results recently obtained through the use of VLBI, in astrophysics and geophysics. This conference is probably unique in bringing together experts in fields as diverse as earthquake hazard reduction and quasar kinematics. VLBI provides the glue that should keep these various fields together for their mutual benefit.

5. REFERENCES

1. Hertz, H. Electric Waves (Dover, New York, 1962).
2. Livingston, D.M. The Master of Light (Scribner's, New York, 1973).