The Velocity of Electromagnetic Waves*

As one of the fundamental physical constants, the velocity of light, or of electromagnetic waves in general, has been the subject of much study. A recent review of the literature on this subject was made by R. T. Birge in *Reports on Progress in Physics*, in 1941. Since that time a number of determinations of the velocity of radio waves has been made whose accuracy closely equals the best measurements for the velocity of light. However, the accuracy of any measurement made to date does not exceed three or four parts in one hundred thousand, while Birge's most probable value is quoted only to about one part in one hundred thousand. Although this has proved adequate for most previous work, the development of radar and its application to geodetic and geographic surveying has made a much higher accuracy desirable. This is the case because the other component required for a radar determination of distance, namely, time of travel of radio waves, can be readily measured with the aid of the quartz crystal oscillator to an accuracy of one part in one million, and accuracies of the order of ten or one hundred times better may be possible. For these reasons, a new review of our knowledge of the velocity of propagation of electromagnetic waves is of value.

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Apart from the early astronomical methods used for measuring the velocity of light, most methods have depended upon modulating a light beam which is transmitted to a distant point, from which it is reflected back on its path. It is then combined with some of the original modulated beam and the resultant signal is observed. This will depend on the modulation frequency used and the distance travelled to the far reflecting mirror. The determinations of Karolus and Mittelstaedt (1928), Hüttel (1937), and Anderson (1937 and 1940), used a Kerr cell to modulate the light beam; all other measurements of the velocity of light have employed a mechanical modulator, most frequently in the form of a rotating mirror. Owing to limitations in maximum speed of such a modulator a light path of some miles is necessary. In Michelson's final measurement, which was concluded by Pease and Pearson (1935), unusual precautions were taken to provide the best conditions over the entire light path. The path was enclosed in a steel tube three feet in diameter and one mile long, which was continuously evacuated to a pressure of a few millimetres of mercury. The use of a Kerr cell in later work has enabled the use of a much higher modulation frequency, usually of some millions of cycles per second, and hence a light path of about a hundred feet only was necessary.

The velocity of radio waves has also been measured many times, but apart from Mercier's measurements of standing waves on parallel wires (1923), no results had been obtained with an accuracy much better than one part in a thousand until radar techniques were developed during the last decade. It is worth noting that Mercier's results are remarkably good considering that radio technique at that time was still in its infancy. Towards the end of the last war two series of measurements of the velocity of radio waves by Smith, Franklin, and Whiting (1947) and by Jones (1947) were undertaken at the Telecommunications Research Establishment, in England, using wartime radar equipment. The results have been announced recently and show reasonable agreement with previous measurements of the velocity of light. Recent work in America in the application of radar to surveying by Aslakson (1946) in which an accuracy of measurement of distance of better than one part in a hundred thousand is claimed, implies that the value of velocity of propagation assumed in this work is correct to at least this order. A further method of measurement of velocity is described by Essen (1947) in a recently published report on work performed at the National Physical Laboratory. A cavity of known dimensions is made to resonate at a known frequency in the microwave region and the velocity of electromagnetic waves is then calculated from the theory of such resonant cavities.

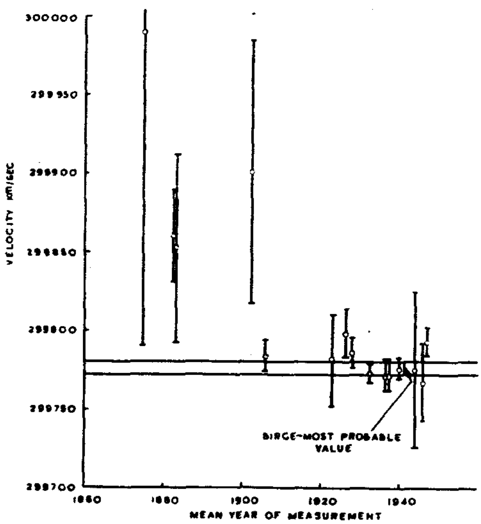
The ratio of the electromagnetic unit to the electrostatic unit of electricity is numerically equal to the velocity of light. A very accurate determination of this ratio was made by Rosa and Dorsey (1907). In this determination the capacity of a condenser consisting of two concentric hollow spheres was calculated in electrostatic units from its dimensions. Its capacity in electromagnetic units was measured in terms of the International ohm by a Maxwell bridge. The final corrected figure for the ratio agrees closely with other values for the velocity of electromagnetic waves.

The following table sets out the principal measurements that have been made over the last century of the velocity of electromagnetic waves *in vacuo*. A corrected value given by Birge for a number of the determinations is included, in addition to the original author's stated value. The basis of the corrections is fully set out in Birge's (1941*a*) paper on the General Physical Constants. The values given

Author	Method	Mean Year of Measurement	Corrected Result Km./sec.	Adopted Probable Error	Original Published Result Km./sec.
Fizeau	Toothed wheel.	1849	315,300	—	315,300
Foucault	Rotating mirror.	1863	298,100	500	298,100 ± 500
Cornu, Helmert	Toothed wheel.	1875	299,990	200	299,990 ± 200
Michelson	Rotating mirror.	1879·5	299,910	50	299,910 ± 50
Newcomb	Rotating mirror.	1882·7	299,860	30	299,860 ± 30
Michelson	Rotating mirror.	1882·8	299,853	60	299,853 ± 60
Perrotin	Toothed wheel.	1902·4	299,901	84	299,901 ± 84
Rosa, Dorsey	Ratio e.m.u./e.s.u.	1906·0	299,784	10	299,710 ± 30
Mercier	Standing waves.	1923·0	299,782	30	299,700 ± 30
Michelson	Rotating mirror.	1926·5	299,798	15	299,796 ± 4
Karolus, Mittelstaedt	Kerr cell.	1928·0	299,786	10	299,778 ± 20
Michelson, Pease, Pearson	Rotating mirror.	1932·5	299,774	4	299,774 ± 11
Hall, Pierce	Standing waves.	193-	299,761	—	299,761
Anderson	Kerr cell.	1936·8	299,771	10	299,764 ± 15
Hüttel	Kerr cell.	1937·0	299,771	10	299,768 ± 10
Anderson	Kerr cell.	1940·0	299,776	6	299,776 ± 14
Mandelstam, Papalexi	Radio waves.	1940	299,980	500	299,900 ± 500
Smith, Franklin, Whiting	Radar pulses.	1944	299,775	50	299,695 ± 50
Jones	Radar pulses.	1946	299,767	25	299,687 ± 25
Essen	Resonant cavity.	1947	299,793	9	299,793 ± 9
Birge	Most probable value, i.e. statistical.	1941	299,776	4	

by Mercier, Smith, *et al.*, and Jones, which related to the velocity in air, have been reduced to *vacuo* assuming the measurements to have been made in dry air at 20° C. and 760 mm. Hg. pressure. This assumption has been made by the author, since no details were given of the actual conditions at the time of the experiments. It is unlikely that the actual conditions would depart from those assumed by an amount sufficient to cause an error of more than two or three parts in one hundred thousand in the quoted value. This is inside the error indicated in the table.

The accuracy figures quoted above for the corrected values are for the most part those given by Birge and as such are the probable errors. The original papers all too frequently give no indication whether the error stated is the probable error, the standard deviation, the limit of uncertainty, or any other value.



The results in the table have been plotted in the accompanying figure along with their probable errors. It was suggested by M. E. J. Gheury de Bray (1927 and 1934) that there was evidence that the velocity of light was varying according to the law $V_{Km/sec} = 299900 - 4T(1900)$years. Subsequently F. K. Edmondson (1934) suggested that the observed points fitted better the law $V = 299885 + 115 \sin 2\pi/40 (T-1901)$. These suggestions were made prior to the publication of Anderson's work. Consideration of measurements of the velocity of radio waves as distinct from light, and later determinations together with allowance for the probable errors of measurement, do little to support this interesting hypothesis that there has been a slow change in velocity over the years. In this respect it is interesting to note statements in the paper by Michelson, Pease, and Pearson (1935) to the effect that they considered that the variations they observed in the values for the velocity of light during their experiments differed from the mean value by rather more than the expected experimental error. They did in fact attempt to discover the cause of these relatively short period fluctuations of the observed values and attempted to correlate them with lunar position or tidal movements which might have caused a change in the length of the light path, but they were unable to obtain any satisfactory correlation.

An important feature of the use of radar methods for the precise measurement of distance is that the velocity of electromagnetic waves will vary with the meteorological conditions over the path traversed. Hence in order that a really accurate determination can be made it is necessary to know exactly the atmospheric conditions along the path. A consideration of these factors indicates that with reasonable precautions corrections can be made to reduce the velocity to *vacuo* so that an accuracy of ten parts in a million can be obtained, but that quite detailed observations of temperature, pressure and water vapour content are necessary before an accuracy of one part in a million can be assured. Recent results obtained in America, as has been mentioned, claim an accuracy of better than ten parts in a million for measurements of distance of from one to three hundred miles. This implies that the value of velocity assumed (not stated, but in the opinion of the author most probably 299776 Km./sec.) is correct to this accuracy. However, an independent check measurement to the same accuracy or better would be highly desirable.

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