THE VELOCITY OF LIGHT

by Carl I. ASLAKSON

In view of the numerous reviews devoted to the velocity of light which have appeared in the literature within the last decade, another is scarcely justified unless it contributes material previously unpublished or presents certain new aspects of the subject. It is hoped that for one or both of these reasons this paper may be of some value.

The value of *c*, the velocity of propagation of electromagnetic waves, is assumed to be independent of frequency. This is generally accepted as true in a vacuum but in a refracting medium such as air, the frequency affects the velocity in the visible spectrum. For the radio frequencies the effect is negligible. This is obvious when the following formulae, adopted by the XIIth General Assembly of the International Union of Geodesy and Geophysics at Helsinki, Finland, are examined.

" ... the velocity of light in vacuo is 299 792.5 ± 0.4 km/sec. "

$$(n_G - 1)\, 10^7 = 2876.04 + \frac{16.288}{\lambda^2} + \frac{0.136}{\lambda^4} \qquad (1)$$

[illegible]

$\frac{c}{n_L}$

$$n_L = 1 + \frac{n_G - 1}{1 + \alpha t} \cdot \frac{p}{760} - \frac{0.55\, e\, (10)^6}{1 + \alpha t} \qquad (2)$$

$$(n_r - 1)\, (10)^6 = \frac{103.49}{T}\, (p - e) + \frac{86.26}{T} \left(1 + \frac{5748}{T}\right) e \qquad (3)$$

n_L = refractive index of air in ambient conditions;
n_G = refractive index of air of group wave length in normal air with 0.03 % CO_2 at normal temperature and pressure;
λ = light group wave-length in microns;
t = temperature in degrees C;
T = temperature in degrees K;
p = atmospheric pressure in mm Hg;
α = coefficient of expansion of air (0.003661);
e = partial water vapor pressure in mm Hg;

Examining Eq. 1, the reason for the frequency effect on light is clear. Scattering occurs when small particles such as water droplets or carbon occur in the air. The wave-length of light is approximately 0.6 microns. Clearly, when the particles in the air are of the order of one tenth or two tenths of the wave-length, the scattering is proportional to $\frac{1}{\lambda^4}$. With somewhat larger particles the effect is less and is proportional to $\frac{1}{\lambda^2}$. When the waves approach the radio frequencies, the terms containing the powers of λ in the denominator become so small as to be negligible. For example, even at the very high frequency of 24 000 mc/s, λ is approximately 1.25 cm or 12 500 microns. The true velocity of electromagnetic waves at any point in the atmosphere is the value of c, the velocity in a vacuum, divided by the index of refraction at that point.

The Velocity of Ground Waves

The preceding paragraphs apply only to the free waves, i.e. the waves which are unaffected by the ground. As the frequency decreases from the upper broadcast band down to 100 kilocycles or less, the propagation velocity is strongly affected by the material in the earth's crust over which the wave is propagated. When these frequencies are used for positioning equipment such as Loran, Lorac, Omega, Raydist or Decca, the conductivity and dielectric constant of the land or water surfaces strongly influences the velocity of the radiation propagation. Hence in making distance measurements with instruments of this type, some means of experimentally determining an " effective " velocity must be employed. These " effective " velocities are as much as 700 km/sec slower than the free wave values and also vary in a complicated manner with the frequency used.

Pressey, Ashwell and Fowler [1] used Decca in England to measure phase velocity of ground-wave propagation over a land path. Their conclusions are given below.

" A value for the mean velocity of waves at a frequency of 127.5 kc/s over a particular land path has been determined as 299 230 km/sec. ... ".

" Measurements of phase made at frequent intervals along the path have provided qualitative data on the variation of velocity with the type of ground ... Changes of velocity with ground conductivity ... are clearly shown; the velocity is greater over high-conductivity ground than over low-conductivity ground. The nature of the path was such that with this method of measurement a useful value for the velocity over any particular homogeneous section of the path could not be determined ".

Despite the foregoing and many other findings of the same nature certain long-wave systems are continually being advanced as capable of making measurements of geodetic accuracy. At best, however, such instruments can only serve a useful purpose for navigation at sea. Even then the changes in temperature and salinity of the sea-water and the effect of even the smallest of intervening islands or other land masses along the path can cause significant changes in the distances measured.

Awakening Interest in the Value of c

Prior to World War II the scientist's thirst for knowledge provided the principal stimulus for seeking greater accuracy in this constant. The limiting accuracy of astronomic measurements made the light-year unit of the astronomer sufficiently accurate and for electronic design purposes the approximate value of $c = 300\,000$ km/sec was quite adequate.

However in the decade following 1940 two developments in science and technology created a new interest in obtaining a more accurate value of c. One development was the new interest in atomic energy where the basic equation is " Energy equals mass times the square of the velocity of light ". ($E = mc^2$). Another was the development of radar and the application of the simple relationship " Distance equals velocity times time ". ($S = vt$). If electronic pulses could be timed with sufficient accuracy and if the velocity were known, it became a simple matter to measure distance by radar. It is interesting to note that certain atomic physicists, on the basis of early experimental results, had begun to question the value of $c = 299\,776$ km/sec which had been accepted for approximately a decade. Also military users of radar had noted systematic discrepancies and they encouraged further research.

The problems of radar were complicated by the fact that existing literature devoted to the effects of the atmosphere on the velocity of radio waves was almost non-existent. Nearly all research had been devoted to signal strength and attenuation of radio waves in the atmosphere but accurate methods of correcting the velocity of propagation for atmospheric changes had been neglected.

The early experimenters striving to increase the accuracy of radar, were forced to study two important effects of the atmosphere on radio waves :

(1) the effect of the atmosphere on the rate of change of the velocity along the path;

(2) the curvature of the path caused by the refraction of the ray through the different layers of the atmosphere.

While the basic physical relationships were known, the actual development of adequate and convenient equations for making the corrections had to be carried out by those engaged in the research. Eventually it was found that the accepted value of c itself was in error.

The fact that those engaged in this research had developed their own correction equations made it difficult for them to suggest that they had discovered an error in the speed of light. The matter was further complicated by the lack of a generally accepted length standard. For distances varying from a few kilometers up to many hundreds of kilometers it was necessary to rely on the work of the geodesist. Previously geodetic measuring accuracy had evaluated only its internal consistency or its " closing errors ". Geodesists had always been conservative when pressed for an estimate of the accuracy of geodetic triangulation. As a rule a linear error of 1 part in 50 000 was estimated. However geodetic specifications usually called for a base-to-base check of 1 part in 25 000.

This specification was commonly interpreted as expressing the accuracy of geodetic triangulation. Completely ignored was the fact that geodetic triangulation was controlled by many other specifications. These were :

(1) The observed triangulation was adjusted by least squares from base to base, the measured lengths being held fixed in the adjustment.

(2) In addition to the above length equation many other conditions were involved, these being :

(*a*) Angle equations involving the triangle closures and the spherical excess;
(*b*) Side equations based on the internal length check in each figure;
(*c*) Azimuth equations to adjust to fixed azimuths;
(*d*) Latitude and longitude equations where previous latitudes and longitudes were held fixed;
(*e*) The LAPLACE equation to correct for the effect of the deflection of the vertical on azimuths.

(3) Finally all observing processes were so designed that the effect of systematic errors were for the most part eliminated.

Despite this, the assessment of first order triangulation as accurate to one part in 25 000 persisted long after electronic distance measuring methods and equipment had been perfected to the point where relative comparisons with geodetic distances were being repeated with a consistency of 1 part in 100 000 or better.

It has since been learned that the accuracy of geodetic triangulation cannot be expressed as a linear function of distance. A number of equations have been suggested to indicate this accuracy. One which is commonly quoted is,

$$\text{Proportional Error} = 1/20\,000\ S^{-1/2} \qquad (4)$$

The error at 100 miles computed by this equation would be 1/200 000.

For physicists engaged in laboratory determinations of c, the problem of a length standard was simpler. They could use highly accurate standard gauges and interferometric methods and thus their results were less open to suspicion. As will be seen, it was only because of the remarkable agreement between certain laboratory determinations and several measurements over longer distances by electronic methods, that the velocity of 299 776 km/sec, which had been accepted for a decade, was finally acknowledged to be too low by approximately 1 part in 20 000.

Methods of Measuring Velocity

The better methods of measuring c can broadly be grouped into four classes.

(1) The determination of the ratio between the electromagnetic and the electrostatic units.

(2) The guided wave methods.

(3) The free-wave methods.

(4) The micro-wave interferometer method which is essentially a free-wave method which also employs wave guides for much of the path.

The Ratio between the Electromagnetic and Electrostatic Units

The ratio method is of interest principally from an historical standpoint. Although a score of attempts to measure c by this method have been made none have attained the accuracy of other techniques because of the enormous difficulty of the experiment. ESSEN [2] states that the earliest determination was by WEBER and KOHLRAUSCH in 1857. As early as 1868 MAXWELL recognized the importance of the constant and said, " The importance of this ratio in all cases in which electromagnetic and electrostatic action is combined is obvious. Such cases occur in the ordinary workings of all submarine telegraph cables, in induction coils, and many other artificial arrangements. But a knowledge of this ratio is, I think, of still greater importance when we consider that the velocity of propagation of electromagnetic disturbances through a dielectric medium depends on this very ratio, and according to my calculations is expressed by the very same number. "

MAXWELL's value was far too low being 284 300 km/sec while WEBER and KOHLRAUSCH obtained the high value of 310 800 km/sec.

The great difficulties of this experiment prevented accurate results from being obtained and an enumeration of the attempts would be pointless. However the remarkable work of ROSA and DORSEY [3] in 1906 is worthy of mention. This famous experiment has been characterized by BIRGE [4, 5] as " one of the most beautifully executed pieces of precision research in the entire history of science. " The published value of this experiment was 299 784 ± 30 km/sec. However the following quotation from a personal communication by Dr. DORSEY to the writer and dated December 4, 1953 is important.

" ... The value we found was $c = 2.9971\ (1 + k)\ 10^5$ km/sec in vacuo. Here k is a small correction depending on the absolute value of the NBS standard ohm. k consists of two terms, a very small one depending on the ratio of the NBS ohm to the International Ohm; and a larger one depending on the ratio of the International Ohm to the Absolute Ohm.

" Soon after our paper was published, SMITH at the National Physical Laboratory, published his determination of the ratio of the British Ohm to the Absolute Ohm. The British and NBS ohms were nearly identical. Hence his measurement gave us at once the value of the major part of the correction k. And not long thereafter the various national ohms were intercompared and the remainder of the k-correction was determined.

" As thus corrected, our value for the velocity in vacuo became 2.9979×10^5 km/sec.

" See H. L. CURTIS, *Bureau of Standards Journal of Research* 3 : 63-64 (RP 83) 1929 :

" Since at the time our paper was published it was generally thought that such work could scarcely be less certain than 1 in 1 000 (0.1 %) we thought it unwise to claim an accuracy exceeding 1 in 10 000 although personally we were of the opinion that the accuracy approached 1 in 30 000. "

This quotation is given at some length because of its historical interest. It also illustrates the desirability of providing additional figures in the result of an experiment even though they may be questioned, providing the authors of the experiment have confidence in their work.

The Guided Wave Methods

Experiments with the guided wave method were first made in the latter part of the 19th century. The early experiments were made by using parallel conductors, commonly known as " lechers " to guide the waves. Inasmuch as the measurements were made prior to the development of modern precision measuring equipment most of the results were inferior. An observation of better accuracy was made by MERCIER in 1923. ESSEN [2] describes the experiment briefly.

" ... MERCIER made a precise determination of velocity by this method using continuous waves at frequencies of 46 mc/s and 66 mc/s. The parallel conductors (lechers) were 11 meters long and tightly stretched between the walls of the room at a distance of 2 meters from the floor and neighboring objects. The movement of the short circuit to give successive resonant positions was measured by an invar tape which could be read to an accuracy of 0.1 mm. The velocity obtained ... after corrections had been applied for the effect of the conductors and the atmosphere gave a free space value of 299 782 ± 30 km/sec.

" It was a remarkably careful piece of experimental work which seems, however, to have attracted little attention. "

The following description of MERCIER's work illustrates the general principles of the guided wave method. For a known frequency the length is measured at the points of resonance. Wave length can then be computed for the group wave. Velocity can then be determined from the relationship that velocity equals frequency times wave length ($v = f\lambda$). The measured frequency is f while λ is the computed wave length.

The use of lecher wires was abandoned in later work and resonant cavities were used. The dimensions of the resonant cavities could be measured with a high degree of accuracy by means of standard gauges with small differential changes being measured interferometrically. Another advantage of using cavity resonators was that they could be easily evacuated, thus obviating the need for observing in air and reducing the results to a vacuum.

The most noteworthy experimentation with cavity resonators was performed by ESSEN [6] and BOL [7]. ESSEN employed 4 frequencies, 5 960, 9 000, 9 500, and 10 830 mc/s. BOL on the other hand used only two frequencies near 3 000 mc/s. The two frequencies used by BOL were just sufficient for a determination while ESSEN made redundant observations. The following results were obtained :

ESSEN	299 792.5 ± 3 km/sec
BOL	299 789.3 ± 0.4 km/sec.

Both measurements were carefully performed, ESSEN's larger quoted error being explained by the fact that he quoted the limiting error. Bol's error assessment was based on estimating a number of individual errors in his work and computing the mean square error.

The puzzling discrepancy between the results of these two observers has generally been attributed to an uncertainty in the effective cavity diameter in Bol's experiment. Cohen, Crowe & Dumond [5] attribute Bol's anomalous result as " due to the possible presence of silver sulphides of an unknown thickness with a conductivity and dielectric constant differing from the values for bulk silver. " This would affect the observed resonant frequency of the cavity. Essen's use of redundant frequencies permitted an assessment of this effect enabling him to compute a correction. Bol, on the other hand, used exactly enough frequencies to determine *c* in the absence of such skin effects which were probably present.

The Free Wave Methods

All determinations of the velocity of light itself and many of the values observed in the radio frequencies have been made with free wave methods. The first observational proof that light traveled with a finite velocity was the famous work of the Danish astronomer Ole Roemer, although Galileo had suspected the truth. Roemer, in 1676, measured the periods of Jupiter's moons and noted that as the earth traveled in its orbit away from the planet, the eclipses of Jupiter's moons occurred later and later. He noted that the differences in the time of the eclipses when the earth was nearest Jupiter and when it was farthest away differed by 1 000 seconds. Roemer could account for this delay only by concluding that it represented the time it took for light to travel the diameter of the earth's orbit. Believing at the time that this diameter was 172 000 miles he concluded that the velocity of light was 172 000 miles per second. It is now known that the diameter of the orbit is larger and Roemer's determination should have been closer to 186 000 miles per second or 300 000 km/sec.

Bradley, an English astronomer, in 1727 also deduced that the velocity of light was finite because of the aberration of light or the displacement of the apparent positions of the stars in the direction of orbital velocity.

The importance of the work of Roemer and Bradley was simply that they both provided experimental proof that the velocity of light was finite.

Early Attempts to Measure Velocity

The two quantities required to measure the speed of light are time and distance. The early attempts to measure this velocity differed mainly in the manner in which the light was " chopped " or " shuttered " into discrete packets or pulses in order to identify particular pulses to be timed. Two methods of shuttering were employed for the early experiments. Fizeau (1849), Cornu (1874), and Perrotin (1902) employed the toothed wheel to break up the light beams into pulses. Foucault (1862), Michelson (1879), (1882), and (1924), and Newcomb (1882) used the rotating mirror method. The principles of these experiments are well known and will not be described. The earliest toothed wheel experiments presented so many technical difficulties that the results could merely confirm the fact that the velocity of light was finite. However between 1879 and 1902 four observations were made which were of importance. They are shown in Table I.

TABLE I

Date	Author	Approx. Distance (meters)	Method	Velocity (km/sec)	Error ± km/sec
1879	MICHELSON	700	Rotating mirror	299 910	50
1882	NEWCOMB	3 700	"	299 860	30
1882	MICHELSON	700	"	299 850	60
1902	PERROTIN	46 000	Toothed wheel	299 880	60
			Mean	299 875	± 55

For the first time a reasonable agreement between different observers and different methods was found.

The Kerr Cell — Photo Cell Shuttering Method

In 1928 KAROLUS and MITTELSTADT developed a new method of chopping the light beam into discrete pulses. Their development was the forerunner of the modern geodimeter. The principle of the Kerr cell operation will not be described in detail. It is sufficient to say that certain transparent insulators such as glass become doubly refracting when placed in a strong electric field. Hence such an insulator of the proper thickness placed in a beam of polarized light between a polarizer and an analyzer will cut off the light by interference. When the electric field is a rapidly alternating one, a cell designed thus operates as a rapidly operating shutter. Such a cell is named after its discoverer, the Scottish physicist, John KERR (1824-1907). BERGSTRAND's geodimeter [8] is the modern surveying instrument which utilizes the Kerr cell.

Between 1924 and 1928 three more important measurements of the velocity of light were made and are listed in Table II.

TABLE II

Date	Author	Approximate Distance (meters)	Method	Velocity (km/sec)	Error (± km/sec)
1924	MICHELSON	35 000	Rotating mirror	299 802	30
1926	MICHELSON	35 000	Rotating mirror	299 798	4
1928	KAROLUS & MITTELSTADT	200	Kerr cell	299 786	30
			Mean	299 795	± 18

MICHELSON's 1926 work gave an original value of 299 796 km/sec. BIRGE later discovered that MICHELSON had incorrectly used the phase velocity refractive index instead of the group velocity (see Eq. 1 & 2) and he revised MICHELSON's value 2 km/sec upward. BIRGE [9] terms this " one of the most inexplicable errors " he had ever encountered. MICHELSON had, in previous work, shown that he was familiar with the distinction between phase and group velocity indices of refraction. In most reviews MICHELSON's published value of 299 796 is quoted, the authors usually being unaware of BIRGE's correction.

Another group of measurements which were made between 1935 and 1941 are shown in Table III.

TABLE III

Date	Author	Approx. Distance (meters)	Method	Velocity (km/sec)	Error (± km/sec)
1935	MICHELSON, PEASE & PEARSON	1 600	Rotating mirror	299 774	11
1937	ANDERSON	170	Kerr cell	299 771	15
1940	HÜTTEL	80	Kerr cell	299 771	10
1941	ANDERSON	170	Kerr cell	299 776	14
			Mean	299 773	± 12.5

The steady decrease in the published values from 1879 to 1941 could not fail to attract attention. A summary is shown in Table IV.

TABLE IV

Dates	Mean values (km/sec)	Mean Errors (± km/sec)	Number of Methods	Number of Observers	Number of Observations
1879-1902	299 875	55	2	3	4
1924-1928	299 795	18	2	2	3
1935-1941	299 773	12.5	2	3	3

It is small wonder that there should be speculation as to the possibility of a secular change in the speed of light. Such a change, however would imply a finite rest mass for the photon, a fact contrary to accepted physical theory.

Up until 1941 BIRGE [10, 11, 12] had made three statistical estimates of the various experiments and in 1944 DORSEY [13] made the most comprehensive analysis that had been made up to that time. These estimates are shown in Table V.

TABLE V

Date	Velocity in vacuo (km/sec)	Author	Reference
1929	299 796 ± 4	BIRGE	10
1934	299 776 ± 4	BIRGE	11
1941	299 776 ± 4	BIRGE	12
1944	299 773 ± 14	DORSEY	13

DORSEY gave little weight to work done previous to 1935 and increased the error estimate to what is now known to be a more realistic value. In spite of the more elaborate evaluation of DORSEY, the BIRGE value of 299 776 was quoted more frequently. The close agreement between the last work of MICHELSON *et al.* and ANDERSON occasioned the following remark in " Fundamental Constants of Physics " [14] in 1957.

" These two measurements with their impressively large number of replicated observations and their excellent (but apparently fortuitous) agreement have misled physicists, including R. T. BIRGE, for about a decade. "

Post World War II Measurements

The increasing use of radar in World War II, particularly the development of blind bombing instruments, spurred further investigation in the velocity of light. In England in 1947, SMITH, FRANKLIN & WHITING [15] and JONES and CORNFORD [16] had used the British bombing instruments G-H and Oboe respectively to make measurements over long distances and had published values of 299 786 ± 50 and 299 782 ± 25 km/sec. These measurements were intended only to indicate that the BIRGE statistical value of 299 776 km/sec then in use was too low, a fact that had been suspected from systematic radar discrepancies. Meanwhile ESSEN [17] who as early as 1943 had claimed, on the basis of cavity resonator measurements, that this value was too low, published a value of 299 793 ± 9 in 1947. BERGSTRAND [8] from early geodimeter measurements had obtained 299 796 km/sec. At the same time the writer, while engaged in research for development of the blind bombing instrument Shoran into a geodetic tool, had found a linear discrepancy with distance. After a search for the source of the discrepancy, the conclusion was reached that it was a scale error caused by the use of the wrong velocity. As a result ASLAKSON [18] published a value of 299 792.4 ± 2.4 km/sec. A summary of all of these new values is shown in Table VI.

TABLE VI

Date	Author	Method	Approx. Frequency (mc/sec)	Value (km/sec)
1947	SMITH, FRANKLIN, & WHITING	G-H	50	299 786 ± 50
1947	JONES & CORNFORD	Oboe	3 000	299 782 ± 25
1948	ESSEN	Cavity resonator	3 000	299 792 ± 3
1948	BERGSTRAND	Kerr cell — Photo-cell	light	299 796 ± 2
1949	ASLAKSON	Shoran	300	299 792.4 ± 2.4

Both ESSEN [19] and BERGSTRAND [20] continued experimentation to improve their methods and equipment. By 1951 three more results had been published by these workers.

TABLE VII

Date	Observer	Method	Frequency (mc/s)	Value (km/sec)
1950	ESSEN	Cavity resonator	10 000	299 792.5 ± 1
1950	BERGSTRAND	Geodimeter	light	299 792.7 ± 0.25
1951	BERGSTRAND	—	light	299 793.1 ± 0.2

ESSEN's work was carefully executed but his quoted error was the limiting error rather than the mean square error.

The Bergstrand Geodimeter

The increase in the accuracy of the geodimeter over the earlier Kerr cell — photo-cell measurements was attributed to a fundamental change in design. In previous designs, readings were made at the peak voltages. It is obvious that the exact time of maximum voltage or the peak of a sine curve is uncertain. In the geodimeter, BERGSTRAND modulated the light beam using a reversed bias during a second half cycle. Thus two opposing voltages cancelled each other producing a null or a point of zero voltage which gave a sharply defined reading. This major change, together with other design improvements [20] resulted in much greater measuring accuracy. BERGSTRAND continued his research and later discovered small sources of error which eventually reduced his 1951 value to close agreement with the 1950 work.

The Microwave Interferometer

One of the most accurate of the modern techniques for measuring *c* is the microwave interferometer, particularly when used in the laboratory. The most noterworthy experiments with this method were the observations of FROOME [21, 22, 23] at the National Physical Laboratory in Great Britain. Particularly significant was FROOME's use of very high frequencies. In 1952 and 1953 he made observations with frequencies of approximately 24 000 mc/s and in 1958 he made a remarkable observation using a frequency of 76 000 mc/s. These new observations were important in that they filled a gap between the longer radio waves and the optical band.

TABLE VIII

Date	Author	Method	Frequency (mc/s)	Velocity (km/sec)
1952	K. D. FROOME	Microwave interferometer	24 005	299 792.6 ± 0.7
1953	K. D. FROOME	"	24 005	299 793.0 ± 0.3
1958	K. D. FROOME	"	76 006	299 792.50 ± 0.10

The 1958 experiment was beautifully executed. It was characterized by a direct determination of the refractive index of air thus obviating the necessity of computing the index from observed values of pressure, temperature, and vapor pressure using the empirical interpolation equations. ESSEN and others consider the 1958 determination of FROOME as the most accurate of modern determinations of *c*. The remarkable consistency of this experiment is shown below and is convincing proof of careful performance.

TABLE IX

HORN Separation (centimeters)	Measured Phase Velocity (km/sec)	Final Value (*) of *c* (km/sec)
629.5	299 796.020	299 792.513
751.5	794.981	792.519
875.0	794.283	792.476
999.0	793.802	792.414
1 120.5	793.583	792.478
1 247.5	793.482	792.588
1 367.5	793.259	792.512
		Mean : 299 792.501 ± 0.059

(*) Corrected for diffraction and reduced to in vacuo values.

Other Recent Data

The literature now contains numerous " measurements of *c* " many of which were made in connection with field geodetic projects. Hence for the most part they were not observations specifically designed to determine the velocity of electromagnetic propagation. In some cases the length standards are open to question. Those published agree remarkably well with presently accepted values of *c* and leads one to surmise that some which agreed less well may not have been published. All of the new values resulting from geodetic field projects in which the geodimeter was used were in agreement with the IUGG value with the exception of the Hiran value published by ASLAKSON. Some of the values are shown below.

TABLE X

Date	Source	Value	Reference
1954	National Mapping Office, Australia	299 792.35	28
1955	Oland Bale Line, Sweden	299 792.4 ± 0.4	27
1953	Ridgeway & Caithness Bases, England	299 792.3 ± 0.5	26
1958	(*) VELICHKO, VASILYEV, KHOMAZA & BOL'SHAKOVAT, U.S.S.R.	299 792.7 ± 0.3	29

(*) This observation was made with the Russian copy of the Swedish Geodimeter. Even a number of base line comparisons made with the South African Tellurometer in various parts of the world gave comparable results despite the fact that the tellurometer is a radio frequency instrument which cannot be compared in accuracy with the geodimeter.

Aslakson, on the other hand, published a value in 1951 [24, 25] which was the result of distance comparisons made during the course of a Hiran project with a much improved Hiran instrument. The value obtained was 299 794.2 ± 1 which deviated considerably from the value toward which all measurements were converging. The discrepancy could probably be attributed to some of the measured geodetic distances which were held fixed in the adjustment.

The close agreement of the values of *c* in all published papers caused some scientists to question them. John A. O'Keefe in May 1951, commenting on a paper by the writer which appeared in *Civil Engineering* [30] said,

" There are several scientific papers in existence noting the fact that the values found for the velocity of light in any given decade seem to group around the same value more consistently than would be expected on the basis of accidental error. This has been attributed to a gradual diminution of the velocity of light or to periodic changes in velocity, but it could be nothing more than the human unwillingness to fly in the face of constituted authority ".

There may be a great deal of truth in O'Keefe's remarks. There is a disturbingly close agreement among the modern published values, regardless of the inherent accuracy of the method used. Furthermore many of the published papers provide little significant information regarding the length standard employed in the measurement.

Future Measurements of c

The question is, " What is the importance of continued research in determining the constant *c* ? ". Some writers have been prompted to suggest that the entire matter of the physical laws pertaining to the velocity of light and to relativity should be reopened for critical examination. In 1957 Rush [31] said,

" Here, then, we have a puzzling situation. The prewar and postwar measurements separated by a decade show a consistant difference of about 16 km/sec. Can it be that it actually increased by 16 kilometers in the 10 year interval ? That a difference of this magnitude between the two self-consistent groups of measurements occurred by chance is not very probable. Yet there are compelling reasons for holding to the belief that *c* must be constant.

" For instance, if the velocity of light is not a constant, then its wavelength or frequency or both must change with time. No systematic changes in wavelengths have been observed. The possibility that frequencies may vary with time is not excluded by any direct evidence we have so far. Perhaps this issue will be settled soon by certain new techniques for comparison of atomic or molecular oscillation frequencies with the motion of the earth, the independent standard to which those frequencies are observed ".

What are some of the new techniques ? We have the atomic clocks, the masers, the lasers and the ability to place scientific satellites in orbit.

Several methods involving satellites are under development for measuring intercontinental distances with great accuracy. The satellites such as *Anna* will provide geodetic data by several independent methods such as photography of a flashing light against a star background, accurate orbital data from range and velocity measurements and even by the use of the minimum sum-distance for determining long distances as in Hiran. The possibilities of the laser systems are so great that scores of organizations in the government and the commercial field are working on various applications. It seems to be but a matter of time before techniques will be devised to improve our present knowledge of the velocity of light.

What is the importance of determining c to a higher order of accuracy ? Certainly the questions posed by O'KEEFE, RUSH and others must be answered. Some scientists have even suggested that the present multitude of elementary " particles " are merely manifestations of ratios of various powers of a few fundamental particles. To prove or disprove this requires a knowledge of many of the atomic constants to a high degree of accuracy. It is most important to refrain from becoming complacent and satisfied with the present state of knowledge.

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