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The Scientific Reliability of Radar Speedmeters

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SYMPOSIUM: RADAR SPEEDMETERS*

PART I

THE SCIENTIFIC RELIABILITY OF RADAR SPEEDMETERS

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INTRODUCTION

The increasing use of radar speedmeters for the apprehension of drivers who exceed the speed limits on our streets and highways is cause for inquiry as to the mode of operation, accuracy, and reliability of this new method of measuring the speed of a moving object. How does the radar method work, what technical problems arise in the use of this equipment, and what operational procedures are recommended in using the radar speedmeter? In trying to answer these questions we shall begin with a brief discussion of the problem of making a measurement of speed, then show how speed may be measured by application of the principles used in the radar speedmeter, next take up the matters of over-all accuracy and reliability of the meter, and finally discuss the operational use of the meter.

THE MEASUREMENT PROBLEM

The problem is to measure the speed of a vehicle moving with respect to a stationary observer. The making of any measurement requires that there be a standard of reference, a means of comparing the quantity to be measured with this standard of reference, and an ob-

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server. How accurately the comparison is made depends upon the means of measurement and the care and judgment of the observer. For example, if we try to measure the length of a fifty-foot stone wall with a linen tape we find that on dry days the length as measured by the tape is slightly less than it is on damp days, when the tape may have shrunk. On the other hand, if we measure the length of the wall with a steel tape, whose length will change only a negligible amount with variations of temperature and not at all with changes of humidity, we have a more accurate measure of the length of the wall. As another example, the accuracy of measurement of an interval of time depends upon the kind of clock used and upon the care of the observer in starting and stopping the clock at the right instants. Similarly, the accuracy of measurement of the speed of a vehicle on the highway by means of a speedometer in another vehicle depends upon how accurately the speedometer has been checked and upon how carefully the patrolman can maintain a constant, safe distance behind the speeding vehicle while he reads the speedometer. The method of measuring speed with a speedometer is a method accepted by the courts. The acceptance of this method is based on two premises:

(1) That the speedometer is accurate, and
(2) That the patrolman knows how to make the measurement.

Hence, in the method of measuring speed by radar the only scientific questions that arise are:

(1) How accurate is the method, and
(2) Does the observer know how to make the measurement with the radar speedmeter?

Accordingly, let us examine the principles of the method.

Principles of the Radar Method

The word *RADAR* is made up from the capitalized letters in the set of words, *RA*dio *D*etection *A*nd *R*anging. Thus, a radar method is one that may be used to detect the presence of a target and determine the distance of that target from the radar set. Radar mehods can also be used to obtain information on the bearing of a target, its altitude, and speed. In all the methods electromagnetic energy in the form of radio waves is radiated from the antenna of the transmitter of the radar set so as to "illuminate" the target; when the target is thus illuminated, it reflects a certain portion of the energy back to the receiver of the radar set. Searching the sky for a target by means of a radar set is like scanning the sky at night with a searchlight. If a part of the light set out by the searchlight comes back to your eyes, we say that something in the sky is reflecting the light, and we deduce from this fact that in the sky there is a cloud or airplane acting as a reflector. All this is a roundabout way of saying that we see a target. In a similar way a radar set is said to "see" a target.

There are several different types of radar systems, all well described in books.[1] Some of the types are quite complex, providing a lot of information about the target; other types are simpler, giving less information. An example of the complex type of radar is the pulse radar set, which sends out pulses of radio waves and measures the time it takes for the pulses to go to the target and come back to the receiver. As the pulses travel at the speed of light, you can find out how far away the target is by multiplying the speed of light by one-half the time elapsing between transmission of a pulse and the reception of its echo. Here, an accurate method of measuring time in millionths of a second has to be incorporated into the radar set. Such a radar method can also give information on the bearing of a target and its angle of elevation in the same manner that a searchlight beam can, because all you have to know is the bearing and elevation of the radar beam.

In contrast to the complexity of the pulse radar method is the simplicity of the method that is used in radar speedmeters. In the speedmeter the radio waves do not move as short disconnected pulses, or groups of wave crests. Instead, the radio wave crests move out from the transmitting antenna continuously without break, and the number of them leaving the antenna each second is constant. The number of these wave crests leaving during each second is called the "frequency" of the radar transmitter. For an average radio broadcasting station the frequency of the main, or carrier, wave that brings music and the sound of voices into our radio receivers at home is about one million wave crests per second. For the radar speedmeter made by a well-known manufacturer the frequency is 2455 million wave crests per second. In scientific work our viewpoint with respect to wave motion is slightly different. Instead of thinking of the number of wave crests passing a point we think rather of the total motion executed by a little particle as it goes up and down from trough to crest of the wave and back again, and we refer to this complete periodic motion as a cycle of events for the little particle. Accordingly we speak then in terms of cycles per second rather than wave crests per second. Thus the frequencies of the broadcasting station and the speedmeter are, respectively, one megacycle per second and 2455 megacycles per second.

This beam of radio waves that is leaving the transmitter of the speedmeter at constant frequency can be directed upon any object in the

[1] RIDENOUR, RADAR SYSTEMS ENGINEERING, c. 5 (New York: McGraw-Hill Book Co., Inc., 1947); *M.I.T. Radition Laboratory Series, No. 1;* HALL, RADAR AIDS TO NAVIGATION 105-110 (New York: McGraw-Hill Book Co., Inc., 1946); *M.I.T. Radiation Laboratory Series, No. 2.*

same way that the beam of a searchlight may be directed upon an object we wish to see. When this beam of radio waves strikes an object, part of the beam may be reflected back toward the receiver part of the speedmeter. If the object is stationary with respect to the radar speedmeter, then the frequency of the "echo" returned by the object to the receiver is exactly the same as the frequency of the beam of radio waves sent out by the transmitter. But if the object is moving with respect to the transmitter, then the frequency of the echo will be different from the frequency of the transmitted beam. If the object—in this case a vehicle—is moving toward the speedmeter, then the frequency of the echo will be greater than that of the transmitter; and if the object is receding from the speedmeter, the frequency of the echo will be less than that of the transmitter. The change of frequency that occurs when the reflecting object is moving with respect to a source of constant frequency is an aspect of an effect that Christian Johann Doppler (1803-1853), an Austrian physicist, called attention to in 1842. The Doppler effect has long been used for measuring the velocity of stars with respect to the earth, light waves being of the same nature as radio waves, but of frequencies of the order of 500 million megacycles per second. More recently the effect has been used to measure the speed of airplanes[2] and even the height of an airplane above the ground.[3] Indeed, the Doppler effect can be noticed for all kinds of motion of a wave-like nature, as for example, sound waves. We have all observed that when we drive past a car whose horn is blowing, the pitch, or frequency, of the sound of the horn falls suddenly just as we pass the car. As we go toward the horn the pitch appears to us to be higher than it actually is, and as we go away from the horn the pitch seems to be lower than it actually is. The same effect would be noticed if we were to remain stationary and the blowing horn were to move. Thus, the Doppler effect is an apparent change in the frequency of a vibration occurring when there is relative motion between the source of the vibration and the receiver of the vibration.

THE USE OF THE DOPPLER EFFECT FOR MEASURING SPEED

Let us suppose that an automobile is moving along the road toward a radar speedmeter from whose antenna radio waves are being emitted at the rate of 2455 million wave crests per second. If the car were standing still it would receive 2455 million wave crests per second, but since it is moving it runs into some wave crests in one second that it

[2] HALL, RADAR AIDS TO NAVIGATION 105-110 (New York: McGraw-Hill Book Co., Inc., 1946); *M.I.T. Radiation Laboratory Series, No. 2.*

[3] CHANCE, HULSIZER, MACNICHOL, AND WILLIAMS, ELECTRONIC TIME MEASUREMENTS (New York: McGraw-Hill Book Co., Inc., 1947); *M.I.T. Radiation Laboratory Series, No. 20.*

would not have met until the next second had it been standing still. Hence, to the car the frequency of the transmitter seems to be slightly greater than 2455 megacycles per second. In reflecting these wave crests back toward the receiver of the radar speedmeter the car becomes a moving source of waves of this slightly higher frequency. But since it is a moving source, the wave crest emitted at the end of a given second does not have to travel so far to the speedmeter as the wave crest emitted at the beginning of the second. The result is an apparent further increase in the frequency already slightly greater than 2455 megacycles per second. The result of these two increases in frequency can be expressed by a very simple, ideal formula as follows:

$$F_R = \frac{c+v}{c-v} F_T, \qquad (1)$$

where F_R = the frequency of the radio waves received by the speedmeter receiver after reflection from the car
F_T = the frequency of the speedmeter transmitter
c = velocity of the radio waves
v = velocity of the car.

At first thought it would seem to be extremely difficult to measure the value of either F_R or F_T down to the last cycle per second in a number that already amounts to 2455 million cycles per second. Fortunately, however, there is another phenomenon, the use of which renders the task quite easy. This is the phenomenon of "beats," used by players of stringed musical instruments for tuning their instruments. If, for example, two adjacent keys on a piano are struck simultaneously, the combination of the two tones will have alternate increases and decreases in intensity, the throbbing of the sound being called "beats." The number of beats per second is equal to the difference of the frequencies of the two vibrating sources. In the same way that beats occur with sound waves of different frequencies so can they also occur with radio waves or light waves of different frequencies.

In the case of the radar speedmeter the antenna will receive radio waves of two different frequencies. It will receive part of the radio wave being emitted by the transmitter at the frequency F_T, and it will receive the wave reflected from the moving car, having frequency F_R. The beat frequency for these two waves will be $F_R - F_T$. Let us see the result of subtracting F_T from F_R, making use of formula (1).

$$F_R - F_T = \frac{c+v}{c-v} F_T - F_T$$

$$= \frac{c+v}{c-v} F_T - \frac{c-v}{c-v} F_T$$

$$= \frac{c + v - c + v}{c - v} F_T$$

$$F_R - F_T = \frac{2v}{c - v} F_T. \qquad (2)$$

For convenience let us denote $F_R - F_T$ by F_D, where the subscript D stands for difference or Doppler. Further, let us observe that v, the velocity of the car, is very much less than c, the velocity of radio waves. For a car going sixty miles per hour, the value of v is one-sixtieth mile per second, while the value of c is 186,281 miles per second. Hence, we may drop the v from the denominator of the right side of equation (2) because it is negligibly small compared with c. Our modified formula is now

$$F_D = \frac{2v}{c} F_T, \qquad (3)$$

and we see that for all practical purposes F_D, the number of beats per second between the transmitted and received waves, is directly proportional to v, the velocity of the car. A further manipulation gives

$$v = \frac{1}{2} \frac{F_D}{F_T} c, \qquad (4)$$

so that we now have the velocity of the car given directly in terms of the beat frequency, the frequency of the transmitter, and the velocity of radio waves. Let us use some numbers in formula (4) to see the simplicity of the calculation. Suppose that F_D is found by measurement to be 500 cycles per second, and suppose that the frequency of the speedmeter transmitter is 2455 million cycles per second. The speed of radio waves is known to be within one or two miles per second of 186,281 miles per second; the speed in miles per hour would be the speed in miles per second multiplied by the number of seconds in an hour, or 186,281 times 3600. The speed of the car will then be given as follows: $v = \frac{1}{2} \times \frac{500}{2{,}455{,}000{,}000} \times 186{,}281 \times 3600 = 68.3$ miles per hour.

Table I shows values of speed of a vehicle corresponding to various values of the number of beats per second as counted by the speedmeter.

Table I

F_D (beats per second)	v (miles per hour)
1	0.14
10	1.37

100	13.7
200	27.3
300	41.0
400	54.6
500	68.3
600	82.0

A calculation made by letting v equal one mile per hour in equation (3) will show that there will be 7.31 beats for each mile per hour of speed of the vehicle, so that for a car going sixty miles per hour, the beat frequency will be 438.6 cycles per second.

From the foregoing it is clear that the speed of an oncoming vehicle may be measured by use of the Doppler effect provided that there is a way of counting the beats. Hence, we come to a brief description of how the beat frequency is measured, after which we will be in a position to discuss the answers to the questions on accuracy of method and knowledge required by the observer to make the measurement.

Measurement of the Beat Frequency

The receiving antenna of the speedmeter receives radio waves of frequency F_R reflected from the moving vehicle, and it also receives a part of the radio waves of frequency F_T emitted by the transmitting antenna. The combination of the waves of the two different frequencies produces in the antenna a small current of high frequency and of an amplitude that varies comparatively slowly, that is, at the beat frequency. This small current passes through a crystal detector, producing a small voltage of the order of a few thousandths of a volt varying in amplitude at the beat frequency. This small voltage is then amplified about one hundred times in a preamplifier. The output voltage of the preamplifier is applied to a section of the electronic circuit that further amplifies the beat wave and in addition transforms the wave shape from a smooth type of variation, such as characterizes the ripples on a pond, into a square type of wave resembling the end-on view of a series of parallel walls with vertical sides, all of equal width and each separated from the next by a distance equal to the width. This squared-off voltage wave now passes to an electronic frequency meter, whose output voltage is applied to a vacuum tube voltmeter. The reading of the vacuum tube voltmeter may appear on either an ordinary indicating meter or an ordinary recording meter. This voltage reading is a measure of the beat frequency and accordingly of the speed. To make the final meter read in terms of miles per hour it is necessary only to graduate a scale in such terms and affix it to the meter. All sections of the entire beat frequency meter—crystal detector, preamplifier, squarer, frequency meter, vacuum tube voltmeter, indicating and recording instruments—are made according to conventional design procedurè.

Accuracy of the Method

In discussing the accuracy of any method of measurement we attempt to state the tolerances involved in the final result. For example, if we measure the length of a fifty-foot wall quickly with a six-inch pocket rule the answer we get might be in error by as much as six inches; that is, the result might be 49.5 feet or 50.5 feet. The error, then, is six inches in a length of 600 inches, which is equivalent to one part in one hundred, or one per cent. If the length of the wall is known to be fifty feet, then the error in measurement, or tolerance, is one per cent. With a steel tape the length of the wall can easily be measured to within one-quarter inch, so that the error is now one-quarter inch in 600 inches, or one part in 2400. We say that we know the length of the wall to within about 0.04 per cent. Hence, in assessing the accuracy of a method of measurement we evaluate the tolerances in the individual parts of the method, add them all together to see what the maximum possible tolerance is, and then claim that the method can be used to make the measurement to within the tolerance found.

To find the tolerances for the radar speedmeter we begin by considering equation (4),

$$v = \frac{1}{2}\frac{F_D}{F_T}c, \qquad (4)$$

The questions are how closely can F_D be measured, how closely is the frequency of the transmitter held at F_T, and how closely do we know the value of c. The value of c is known to be within one or two miles per second of 186,281 miles per second, so that the tolerance in c is at the most about two in 200,000, or 0.001 per cent. The frequency of the transmitter can be set to within 0.05 per cent of 2455 megacycles per second. The characteristics of the oscillating circuit of this transmitter are such that if its frequency were to try to shift more than about 0.1 per cent, the circuit would not oscillate. Hence, the tolerance for F_T is very small. With regard to the measurement of F_D, small errors can result from changes in the voltage of the battery used to supply electric power to the part of the system involving the squarer, the frequency meter, and the vacuum tube voltmeter. However, there are provisions for adjusting the speedmeter to read correctly after it has been set up "on location" so as to take account of changes of battery voltage. The operator has merely to note from time to time whether or not the pointer on the indicating or recording instrument stands at zero when no vehicle is moving within the operating zone of the speedmeter. If the pointer does not stand at zero he makes it do so by a simple mechanical adjustment. A consideration of all possible changes in final reading of the instrument due to changes in battery voltage leads to the conclusion that the speedmeter will read speeds to within two miles per hour. Compared with this, the one-tenth per cent tolerance in F_T, equivalent to 0.06 mile per hour for v equal to 60 miles per hour, is negligible.

Another factor affecting the accuracy of measurement has to do with the actual application of the instrument rather than with technical aspects of the instrumentation. Ideally, formula (1) is valid when the direction of motion of the car is along the line of sight between the car and the speedmeter. As such a condition is not usually possible, there is an angle A between the direction of motion of the car and the line of sight, so that the value of v is more accurately given by formula (5) below,

$$v = \frac{1}{2}\frac{F_D}{F_T}\frac{c}{\text{cosine } A}. \quad (5)$$

The magnitude of the cosine A term may be seen from the following example. Assume that a car is 175 feet from the speedmeter, that it is traveling along the center line of a road 50 feet wide, and that the speedmeter is set up 10 feet from the edge of the road. Then the factor, cosine A, will be 0.98 for all practical purposes of calculation. If the speedmeter reads 70 miles per hour, the true speed of the car is 71.4 miles per hour. In actual practice the meter is placed closer to the road, but it will always read slightly less than the true speed unless it is directly in the path of the moving vehicle.

Certain additional technical questions arise as to the accuracy of the method, some of them having to do with the speedmeter itself, others having to do with the operational use of the method. For example, the meter should be allowed to warm up for a period of five to ten minutes before being put to work. The operating zone of the meter covers a span of about 200 feet along the road, so that a car may enter this zone at that distance and stay within the view of the meter until it is almost abreast of it. After a car enters the zone it takes the meter about one-fifth second to respond. As regards possible zero shifts arising after the meter has been properly set up and which have not been adjusted out by the operator, the effect is additive. For instance, if the pointer of the meter reads five miles per hour with no car in its zone, and if then it reads 65 miles per hour when a car passes through, the actual speed of the car is 60 miles per hour. Diathermy apparatus in the vicinity can give false readings, which would be noticed as sudden jumps to say seven miles per hour at switching-on of the diathermy machines, and sudden drops back to zero at switching-off. While such effects can be zeroed out, their intermittent nature more or less precludes the value of doing this, and the operator would do well simply to note when the effect is present or absent in making his speed measurements.

An important feature of the speedmeter is that it will read the higher of the speeds of two cars running simultaneously through the zone at different speeds. If two cars are running abreast of each other at the same speed through the zone the speedmeter cannot tell which car is being observed, but its reading will be the speed of either of them. It is then up to the operator to ascertain that the cars are traveling abreast of each other. If one is passing the other the speedmeter reads the higher of the two speeds. This raises the question of what happens if a car is going through the zone in the other direction. The meter reads the speeds of both oncoming and receding vehicles with equal accuracy. However, a car traveling along the other side of the road, going in a direction opposite to that of the cars being observed, will be farther away when it is in the operating zone of the meter than one in the lane being observed, and will reflect back a much weaker signal than that coming from an approaching car. The effect due to receding cars can be largely eliminated by keeping the speedmeter within about three feet of the edge of the road and by pointing its beam more or less down the lane being observed. On recording meters there is a difference between the records of approaching and receding vehicles, when a certain orientation of the speedmeter is used.

Swinging signs, swaying trees, and flying birds can give momentary small readings of five to twenty miles per hour, but the readings are of short duration and can be properly interpreted; in any event their effect is not additive, owing to the property of the meter that it reads the highest velocity it observes.

As to aging of the parts, the general long-time effect would be for the speedmeter to read less than actual values. In fact the effect of lowering battery voltage during operation, the gradual wearing out of vacuum tubes, and the use of the meter at the side of the road instead of in the direct path of a vehicle point to its giving values that are, if anything, less by one or two miles per hour than the true speed, rather than higher values.

The accuracy of the meter can be measured in the laboratory without recourse to any specialized equipment. As was seen in equation (4) the meter is in essence a beat frequency meter, whose readings are given in miles per hour instead of in beats per second. Thus, any electronic audio oscillator, whose frequency range has been properly checked, can be used to check the readings of the speedmeter. For example, when an alternating voltage of 500 cycles per second is applied at the proper point in the meter, the indicator should read 68.3 miles per hour. However, as the speedmeter has a radio transmitter, its operation comes under the jurisdiction of the Federal Communications Commission, which requires that any person who does work on the transmitter possess a first or second class commercial radio operator's license. In view of this requirement, all such checking of accuracy of the speedmeter is best left in the hands of one legally qualified to do so.

Operational Use of the Meter

Having discussed the question of general accuracy of the method, we come to the question of the knowledge required by the observer to use the instrument. In the opinion of the author the average person engaged in traffic control work can learn to use the radar speedmeter after about one and one-half to two hours of instruction. He need not know the details of design and construction any more than he needs to know those of the speedometer on his patrol car. It should be assumed that he has been provided with an instrument of sufficient accuracy; after that, proper and adequate use of it depends upon his care and judgment.

Accordingly, from a scientific point of view, the author recommends certain operational procedures as far as the speedmeter and its use are concerned. Such procedures include the checking of the speedmeter before and after use in each location, the keeping of records, and other details.

It is important to check the meter for accuracy each time it is set up for use; if the meter is to be used at two sites in one morning then it should be checked at each site to avoid the contention that the meter was thrown out of adjustment during transit. The meter should be checked before the beginning of the period of observation of a highway and at the end of the period. In scientific work it is usual to assume that if a given instrument reads correctly at the beginning and ending of a set of measurements, its readings during the interval were also correct. The check can be made by having a car with calibrated speedometer run through the zone of the meter twice, once at the speed limit for the zone and once at a speed ten or fifteen miles per hour greater. As the test car goes by the meter the driver can notify the operator of the meter what his speed is. If the difference between the speedometer reading and the radar meter reading is more than two miles per hour, steps should be taken to see why this is the case and to remedy the matter. Such a test naturally requires a periodic checking of the speedometer of the test car. If such a procedure is carried out each time the radar meter is set up, the check measurements made with the automobile speedometer become supporting evidence.

It is highly advisable to record all pertinent information regarding an observation at the time it is made because of the difficulty of remembering details. It is therefore desirable to use a recording meter for speed measurments. Good scientific procedure requires the following information to appear on the recording chart: date and time of starting a test; name of the operator of the meter; names of other observers and their duties; number of the speedmeter; number of the car in which the meter is installed; the weather conditions. All of this can be written down in less than a minute; its entry at the time of observation can save hours of wrangling later. When it is decided that a given car is to be apprehended the meter operator should put a pencil mark beside the speed indication on the recording chart paper as he watches the car go by, call out over the radio telephone to his partners the speed, color, and kind of car, some part of the license number if possible, and then write on the chart paper this information and the time and his initials. These notes should be corroborated by the persons in the apprehending car by telephone so that all details get completely entered. Thus, the speed indication recorded on the chart will have permanently associated with it the details essential in making the charge. Similar information should be entered on the chart when check runs are made. At the end of each day the chart record for the day should be rolled up, have a tag affixed to it bearing the date of the record, and be placed in a safe. A log book should be kept to show the location, date, times of beginning and ending of observation of traffic, names of all patrolmen concerned, and the speed limit at the location. Records should not be kept on scrap paper and then copied, for errors may be made in copying. If errors are made in writing down information, a line should be drawn through the incorrect parts, and corrections entered with a notation as to why they were made and by whom. It is recommended that the operator of the meter and the people in the apprehending car be within sight of each other so that the operator of the meter can see the apprehended car and signal ahead whether or not the right car has been stopped.

Conclusion

The Doppler effect has been used for approximately a century for the determination of the speed of stars, and for over a decade for measuring the speed of airplanes and finding their height above the ground. Now this effect is being used for the measurement of the speed of objects traveling over the ground. The relation between the speed of an object with respect to a radar speedmeter and the Doppler beat frequency is direct. A speedmeter has been constructed with the use of a number of conventional electronic sections so as to give readings of speed within one or two miles per hour of the actual speeds. The value of the evidence it can furnish will depend largely on how carefully that evidence was correlated with other supporting evidence at the time it was obtained.