Analysis of Target-Speed Determination with Doppler Radar

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Abstract—**The response of the Doppler radar speed meter was analyzed when there were two or more targets in a radar beam. When there are two targets of equal size and equal speed there is a fading condition and under a special condition, the radar becomes inoperative. When many targets with various speeds and sizes appear in a radar beam, the speed-meter output will fluctuate and the output represents either the speed of one of the targets or the average speed of all of them or something else.**

The speed meter is not likely to register the speed of the target with the highest speed as commonly believed. There is no theoretical assurance that the speed meter is registering the wanted target's speed. The fading condition, the fading period, the speed-meter fluctuation frequency, and the speed-meter response to the actual target speeds were theoretically analyzed. Traffic-police radar was mainly used for examples.

I. Introduction

THE principle of target-speed determination with Doppler radar for a single target is simple and it is explained in most textbooks on radars [1]. If the radar receives echoes from more than one target simultaneously, rather complicated problems arise [2]–[6] and a careful interpretation of the speed-meter reading is necessary. For example, a millimeter-wave ultrahigh-definition radar utilizes an antenna of beamwidth on the order of 10 minutes of arc [7]. At a distance of 10 miles away from the antenna, the beam covers a width of 153 feet. The beamwidth of most Doppler radars used by police for traffic speed determination is 5 degrees [8]. At a distance of 1500 feet, the beam covers a width of 132 feet. Therefore, there are frequent chances that more than one target will appear in the beam at the same time. In the Doppler radar, the Doppler shift of the echo frequency is proportional to the target speed. If echoes come from more than one target, the echoes interact with each other and they produce erroneous results in the speed determination. For police radar, this error has often been argued in the courts. Quite a complete discussion on the single-target problem has been published in literature [9]–[17].

To the author's knowledge, *no* analysis of the multiple-target problem of Doppler radar speed-determination methods has been published. In this paper, detailed theoretical consideration is given to the Doppler radar speed-measuring technique when more than one target appears in the radar beam simultaneously.

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II. Problems of the Doppler Radar Speed Meter

The Doppler frequency of a Doppler radar speed meter due to an echo from a moving target with the velocity u is given by [1], [2], [10], [11]

$$f_d = \frac{2f_0}{c} u \tag{1}$$

where f_0 is the carrier frequency of the radar and c is the velocity of light. Usually, this signal appears at the output of the mixer and is amplified, pulse-shaped, and fed into a frequency counter, the output of which is calibrated to the speed of the moving target in such a way that [18]

$$u_m = \frac{\lambda_0}{2} f_d \tag{2}$$

where λ_0 is the wavelength of the carrier frequency of the radar. Therefore, the speed-meter reading u_m is entirely dependent on the Doppler frequency f_d rather than the actual target speed u. If the radar is working normally and there is only one moving target in the radar's beam, the Doppler frequency f_d is due to the moving target. Therefore, the speed-meter reading u_m is the target speed u. If the radar has a noise trouble either internally or externally caused or if two or more targets with different speeds and different directions appear in the radar beam simultaneously, the signal frequency f_d is not necessarily produced by the wanted target alone. Therefore, the speed-meter reading u_m is not necessarily the wanted target's speed u. The signal frequency f_d includes a resultant of Doppler echoes from different moving targets in the radar beam.

III. General Case

If the number of targets in the radar beam is m, then the voltage that appears at the mixer in Doppler frequencies due to the number of echoes is given by

$$\begin{aligned} \dot{v} &= \sum_{n=1}^{m} v_n e^{j(\omega_n t + \phi_n)} \\ &= \sqrt{\left\{\sum_{n=1}^{m} v_n \cos(\omega_n t + \phi_n)\right\}^2 + \left\{\sum_{n=1}^{m} v_n \sin(\omega_n t + \phi_n)\right\}^2} \\ &\quad \cdot \exp\left\{ j \tan^{-1} \frac{\sum_{n=1}^{m} v_n \sin(\omega_n t + \phi_n)}{\sum_{n=1}^{m} v_n \cos(\omega_n t + \phi_n)} \right\} \end{aligned} \tag{3}$$

where v_n, ω_n, and ϕ_n are the magnitude, Doppler angular frequency, and phase of the mixer output voltage, respectively, due to the echo from the nth target. As seen in (3), the output is amplitude-modulated and phase-modulated. Generally,

$$v \neq v_n \tag{4}$$

and the resultant frequency

$$\omega \neq \omega_n \tag{5}$$

$$\left(2\pi f = \frac{4\pi}{\lambda_0} u_m\right) \neq \left(2\pi f_n = \frac{4\pi}{\lambda_0} u_n\right) \tag{6}$$

which implies that

$$u_m \neq u_n \tag{7}$$

and therefore, the speed-meter reading u_m is not the target speed u_n if the nth target is the wanted target. In the above discussion, it was assumed that the frequency counter was working accurately and did not skip even though the signal was comparable to or less than the noise level. It was also assumed that there was no spurious noise. These assumptions also apply to the following discussions.

IV. Special Cases

A. Two-Target Problems

In this case, it is assumed that there are two targets in the radar beam at the same time. The radar output is analyzed for various types of targets. In this discussion, the apparent size of the target is defined by the magnitude of the echo but it does not necessarily coincide with the physical size of the target.

1) The case of the same speed and same size: If two targets of equal size are moving with the same velocity in the radar beam, the mixer output of the radar is

$$\begin{aligned} \dot{v} &= v_1 e^{j(\omega_1 t + \phi_1)} + v_2 e^{j(\omega_2 t + \phi_2)} \\ &= v_1 e^{j(\omega_1 t + \phi_1)}\left(1 + \frac{v_2}{v_1} e^{j\{(\omega_2 - \omega_1)t + (\phi_2 - \phi_1)\}}\right). \end{aligned} \tag{8}$$

Since $v_1 = v_2$ and $\omega_1 = \omega_2$,

$$\dot{v} = v_1(1 + e^{j(\phi_2 - \phi_1)})e^{j(\omega_1 t + \phi_1)}. \tag{9}$$

This shows that

$$u_m = \frac{\lambda_0}{2} f_1 = \frac{\omega_1 \lambda_0}{4\pi} = \frac{4\pi}{\lambda_0} u_1 \frac{\lambda_0}{4\pi} = u_1 = u_2. \tag{10}$$

In this case the speed meter indicates exact target speed. However, when

$$\phi_2 - \phi_1 = \pm\pi, \pm 3\pi, \pm 5\pi, \cdots, \pm(2n+1)\pi \tag{11}$$

where n is an integer,

$$\dot{v} = 0. \tag{12}$$

This means that the targets do not produce the output to the radar. This is the condition of "fading." If the separation of the targets in the direction of the radar beam is D, the "fading distance" that makes the radar output disappear is given by

$$\phi_2 - \phi_1 = \omega_1 \cdot \frac{2D}{c} = (2n+1)\pi \tag{13}$$

or

$$D = \frac{(2n+1)c\pi}{2\omega_1} = \frac{(2n+1)c^2}{8 f_0 u_1} \quad \text{(MKS unit)}. \tag{14}$$

The fading distance D is plotted for various target speeds U_1 in Fig. 1. In this figure, a typical traffic-police radar frequency $f_0 = 10.525$ GHz and a reasonable target-speed range were chosen. In this example, (14) is reduced to

$$D = \frac{1480(2n+1)}{u_1} \quad \text{(miles)} \tag{15}$$

where the unit of target speed is mi/h. As seen from Fig. 1, practically, the fading does not occur in the traffic radar for surface vehicles but the fading will be a problem for high-speed supersonic aircraft and space vehicles or ICBM.

In (8), discussion was performed with the assumption that both echoes from the targets reach the radar. The fading will occur even before the echoes reach the radar under a certain condition. If the phase difference of the radar carrier waves from Targets 1 and 2 $\Delta\varphi$ is an odd multiple of π radian, the echoes fade away and the radar does not register any speed.

$$\Delta\varphi = (\beta_0 + \beta_r)D = \left(\frac{2\pi}{\lambda_0} + \frac{2\pi}{\lambda_r}\right)D = (2n+1)\pi \tag{16}$$

where

$$\beta_r = \frac{2\pi}{\lambda_r} = \frac{2\pi(f_0 + f_d)}{c} \tag{17}$$

is the phase constant of the echo. Therefore,

$$\frac{2\pi f_0}{c}\left(1 + \frac{f_0 + f_d}{f_0}\right)D = (2n+1)\pi \tag{18}$$

or

$$\frac{2\pi f_0}{c}\left(2 + \frac{f_d}{f_0}\right)D = (2n+1)\pi \tag{19}$$

$$D = \frac{(2n+1)\lambda_0}{2\left(2 + \frac{f_d}{f_0}\right)}. \tag{20}$$

In most Doppler radar $f_d/f_0 \ll 1$; therefore,

$$D \approx \frac{\lambda_0}{4}(2n+1). \tag{21}$$

For traffic radar, $\lambda_0 \approx 3$ cm. The fading will occur when the target distance is every odd multiple of 0.75 cm. This means that there is considerable chance or probability of fading occurring.

2) The case of the same speed and different size: In this case, $\omega_1 = \omega_2$ but $v_1 \neq v_2$ in (8); that is,

$$\dot{v} = v_1 e^{j(\omega_1 t + \phi_1)}\left(1 + \frac{v_2}{v_1} e^{j(\phi_2 - \phi_1)}\right). \tag{22}$$

Therefore, the reading of the radar speed meter is correct and no possibility of fading exists.

3) The case of the different speed and same size: In this case, $\omega_1 \neq \omega_2$ but $v_1 = v_2$ in (8); that is,

$$\dot{v} = v_1 e^{j(\omega_1 t + \phi_1)}(1 + e^{j\{(\omega_2 - \omega_1)t + (\phi_2 - \phi_1)\}}). \tag{23}$$

The above equation shows that the radar registers the speed of Target 1 and there is a fading time when

$$(\omega_2 - \omega_1)t + (\phi_2 - \phi_1) = \pm\pi, \pm 3\pi, \pm 5\pi, \cdots, \pm(2n + 1)\pi \tag{24a}$$

or

$$t = \frac{\pm(2n + 1)\pi - (\phi_2 - \phi_1)}{\omega_2 - \omega_1}. \tag{24b}$$

If the fading period Δt is defined so that

$$\delta \equiv 1 - \mathrm{Re}\,|e^{j(\omega_2 - \omega_1)\Delta t}|, \tag{25}$$

then

$$\Delta t \equiv \frac{\cos^{-1}(1 - \delta)}{\omega_2 - \omega_1} = \frac{c \cos^{-1}(1 - \delta)}{4\pi f_0 (u_2 - u_1)}. \tag{26}$$

In Fig. 2, the value of fading period Δt is plotted against the target-speed difference $(u_2 - u_1)$ for a typical traffic-police radar frequency. In this case, if u_1 and u_2 are in miles per hour ($f_0 = 10.525$ GHz, $\delta = 0.5$.

$$\Delta t = \frac{5.31 \times 10^{-3}}{u_2 - u_1} \quad \text{(seconds)}. \tag{26a}$$

Most speed-meter indicators cannot faithfully follow this order of quick fading. Therefore, if the fading problem is involved, the speed meter most likely indicates a speed less than the actual speed of Target 1.

The curve shown in Fig. 2 suggests that if $u_2 = u_1$, there is a possibility of complete fading as shown in Section IV-A.1.

If (8) is manipulated differently, a different conclusion results. In (8),

$$\dot{v} = v_2 e^{j(\omega_2 t + \phi_2)}\left(1 + \frac{v_1}{v_2} e^{j\{(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\}}\right) \tag{27}$$

and in this case, $v_1 = v_2$; therefore

$$\dot{v} = v_2 e^{j(\omega_2 t + \phi_2)}(1 + e^{j\{(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\}}). \tag{28}$$

The above equation indicates that the radar speed meter shows the speed of Target 2 instead of the speed of Target 1. There is a fading time as in the previous case. In this case, the radar speed-meter needle oscillates with a frequency of $(\omega_1 - \omega_2)/2\pi$ if the targets' speed difference is small enough and the needle's mechanical time constant is small enough to follow the output change.

If the time constant of the speed-indicating system is too large for the rapid change of the radar output, it is likely that the radar speed-meter reading will indicate the average speed of Target 1 and Target 2 applying (3) for $n = 1$ and 2,

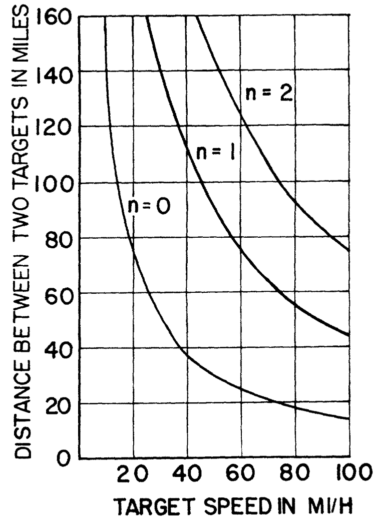

Fig. 1. Fading distance for a Doppler radar.

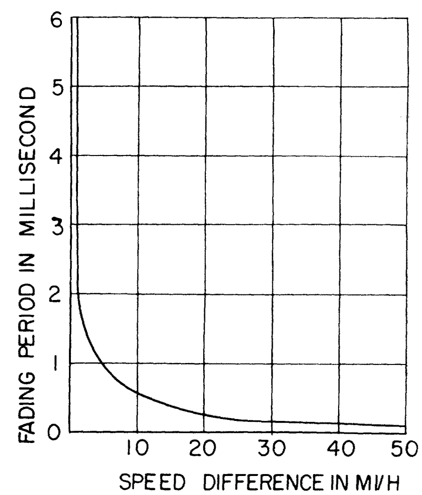

Fig. 2. Fading period for traffic-police radar.

$$\dot{v} = \sqrt{2}\, v_1 \sqrt{1 + \cos\{(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)\}} \cdot \exp\left(j\frac{\phi_1 + \phi_2}{2}\right) \cdot \exp\left(j\frac{\omega_1 + \omega_2}{2}t\right) \tag{29}$$

and therefore

$$u_m = \frac{u_1 + u_2}{2}. \tag{30}$$

The speed meter shows the average speed of both targets at the peak of deflection. The needle fluctuates at the frequency of $(\omega_1 - \omega_2)/2\pi$. In Fig. 3, the relationship between speed-meter reading and possible target speed is plotted. As seen in this figure, there is a chance that the slower target will be caught by mistake by police radar for a traffic-speed violation.

4) The case of different speed and different size: From (8), the mixer output voltage is

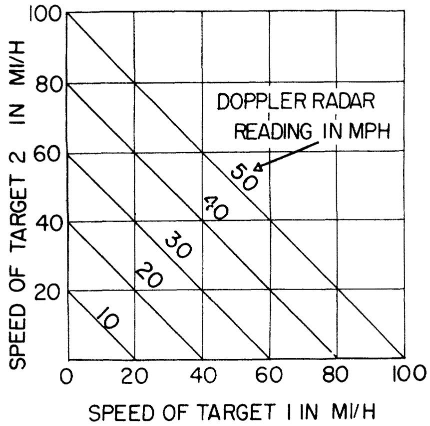

Fig. 3. Response of traffic-police radar for various target speeds.

$$\dot{v} = v_1 e^{j(\omega_1 t+\phi_1)}\left(1 + \frac{v_2}{v_1} e^{j\{(\omega_2-\omega_1)t+(\phi_2-\phi_1)\}}\right) \tag{31}$$

or

$$\dot{v} = v_2 e^{j(\omega_2 t+\phi_2)}\left(1 + \frac{v_1}{v_2} e^{j\{(\omega_1-\omega_2)t+(\phi_1-\phi_2)\}}\right) \tag{32}$$

or from (3)

$$\dot{v} = \sqrt{v_1^2 + v_2^2 + 2v_1v_2 \cos\{(\omega_1-\omega_2)t + (\phi_1-\phi_2)\}} \cdot \exp\left(j \tan^{-1} \frac{v_1 \sin(\omega_1 t+\phi_1) + v_2 \sin(\omega_2 t+\phi_2)}{v_1 \cos(\omega_1 t+\phi_1) + v_2 \cos(\omega_2 t+\phi_2)}\right). \tag{33}$$

The above analysis shows that the speed-meter needle fluctuates with a beat frequency of two Doppler frequencies due to the echoes. The maximum indication will be the speed of either Target 1 or Target 2 or it will switch back and forth between the two speeds or be something else that is neither the speed of Target 1 nor of Target 2. This explains Brantley's experimental results (u_1 = 35.5 mi/h, u_2 = 21 mi/h and u_m = 24 mi/h). In Fig. 4 the fluctuation frequency of the needle $(\omega_1 - \omega_2)/2\pi$ is plotted for various target speeds according to the following equation for f_0 = 10.525 GHz.

$$f_f = \frac{\omega_1-\omega_2}{2\pi} = \frac{2f_0}{c}(u_1 - u_2) \qquad \text{(MKS unit)} \tag{34}$$

or

$$f_f = 31.4\,(u_1 - u_2) \qquad \text{Hz } (u_1, u_2, \text{mi/h}). \tag{35}$$

If the speed-meter pointer cannot follow the fluctuation because the fluctuation frequency is too large, the operator is likely to read some average value that is not the target's speed. If the fluctuation is not so fast, the operator will have difficulty reading the meter. If the fluctuation is slow enough to allow the operator to read the peak deflection precisely, the meter reading will be the speed of either Target 1 or Target 2 or something else. From (33) it is very difficult to realize what the third case will be. It is likely that when $v_1 \gg v_2$, the speed meter registers the speed of Target 1 and vice versa, and if the $v_1 = v_2$ the situation was discussed in case IV-A.3. It should be noted that the fluctuation frequency is in the range of the Doppler frequency utilized for the speed measurement as seen in Fig. 4. Therefore, the fluctuation frequency cannot be filtered. It happens quite often that the fluctuation is not clipped. In this case there is a chance that the fluctuation frequency will be counted by the speed meter instead of ω_1 or ω_2.

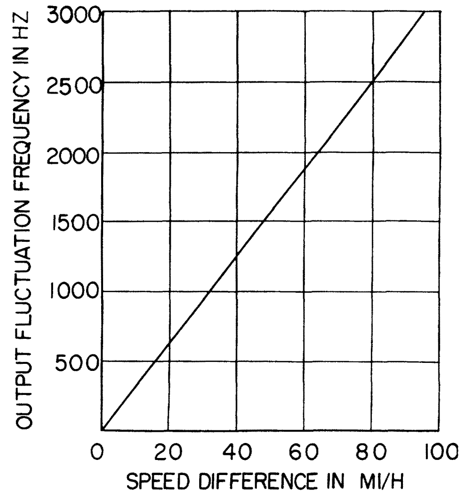

Fig. 4. Fluctuation frequency of the Doppler output of traffic-police radar.

B. *Three-Target Problems*

1) The case of the same speed and same size: The mixer output due to three echoes is

$$\dot{v} = v_1 e^{j(\omega_1 t+\phi_1)} + v_2 e^{j(\omega_2 t+\phi_2)} + v_3 e^{j(\omega_3 t+\phi_3)}. \tag{36}$$

If the targets are the same size and are moving with the same speed, $v_1 = v_2 = v_3$ and $\omega_1 = \omega_2 = \omega_3$ and therefore,

$$\dot{v} = v_1 e^{j\omega_1 t}(e^{j\phi_1} + e^{j\phi_2} + e^{j\phi_3}). \tag{37}$$

The speed meter registers the targets' exact speed but there is a chance of fading when

$$e^{j\phi_1} + e^{j\phi_2} + e^{j\phi_3} = 0, \tag{38}$$

practically there will be small probability of achieving the condition stated in (38).

2) The case of different speed and different size: The radar speed meter registers one of the following possibilities. In (6)

$$\dot{v} = v_1 e^{j(\omega_1 t+\phi_1)}\left\{1 + \frac{v_2}{v_1} e^{j\{(\omega_2-\omega_1)t+(\phi_2-\phi_1)\}} \cdot \left[1 + \frac{v_3}{v_2} e^{j\{(\omega_3-\omega_2)t+(\phi_3-\phi_2)\}}\right]\right\} \tag{39}$$

or

$$\dot{v} = v_1 e^{j(\omega_1 t+\phi_1)}\left\{1 + \frac{v_3}{v_1} e^{j\{(\omega_3-\omega_1)t+(\phi_3-\phi_1)\}} \cdot \left[1 + \frac{v_2}{v_3} e^{j\{(\omega_2-\omega_3)t+(\phi_2-\phi_3)\}}\right]\right\} \tag{40}$$

or

$$\dot{v} = v_2 e^{j(\omega_2 t+\phi_2)}\left\{1 + \frac{v_3}{v_2} e^{j[(\omega_3-\omega_2)t+(\phi_3-\phi_2)]} \cdot \left[1 + \frac{v_1}{v_3} e^{j[(\omega_1-\omega_3)t+(\phi_1-\phi_3)]}\right]\right\} \tag{41}$$

or

$$\dot{v} = v_2 e^{j(\omega_2 t+\phi_2)}\left\{1 + \frac{v_1}{v_2} e^{j[(\omega_1-\omega_2)t+(\phi_1-\phi_2)]} \cdot \left[1 + \frac{v_3}{v_1} e^{j[(\omega_3-\omega_1)t+(\phi_3-\phi_1)]}\right]\right\} \tag{42}$$

or

$$\dot{v} = v_3 e^{j(\omega_3 t+\phi_3)}\left\{1 + \frac{v_1}{v_3} e^{j[(\omega_1-\omega_3)t+(\phi_1-\phi_3)]} \cdot \left[1 + \frac{v_2}{v_1} e^{j[(\omega_2-\omega_1)t+(\phi_2-\phi_1)]}\right]\right\} \tag{43}$$

or

$$\dot{v} = v_3 e^{j(\omega_3 t+\phi_3)}\left\{1 + \frac{v_2}{v_3} e^{j[(\omega_2-\omega_3)t+(\phi_2-\phi_3)]} \cdot \left[1 + \frac{v_1}{v_2} e^{j[(\omega_1-\omega_2)t+(\phi_1-\phi_2)]}\right]\right\} \tag{44}$$

or, from (3),

$$\dot{v} = \sqrt{\left\{\sum_{n=1}^{3} v_n \cos(\omega_n t + \phi_n)\right\}^2 + \left\{\sum_{n=1}^{3} v_n \sin(\omega_n t + \phi_n)\right\}^2} \cdot \exp\left(j \tan^{-1} \frac{\sum_{n=1}^{3} v_n \sin(\omega_n t + \phi_n)}{\sum_{n=1}^{3} v_n \cos(\omega_n t + \phi_n)}\right). \tag{45}$$

The above analysis shows that the speed-meter reading is the speed of either Target 1, Target 2, Target 3, or something else given by (45). The speed meter fluctuates in a rather complicated fashion if the limiter is not working correctly or the magnitude of fluctuation exceeds the design limit of the limiter. It is likely that the speed meter will register the speed of the largest target as seen from the above equations. If all three targets are comparable in size, by combining the echoes from two targets and comparing this combination to the rest, the problem is reduced to the two-target problem of different size and different speed, which is (31), (32), and (33). That is to say, the speed meter is likely to register the average speed of any pair of targets. The pair producing the largest amount of echo is most likely to be tracked.

C. Four-or-More-Target Problems

When four or more targets appear in the radar beam simultaneously, a similar analysis as stated for the three-target problem is applicable. The speed-meter reading is not necessarily equal to the wanted target's speed unless the wanted target produces a distinctly large echo in comparison with other targets, or all the targets are moving at the same speed. In this case, there will be fluctuation problems on the speed-indicating needle.

V. Remarks

The above analysis shows that when many targets are in a radar beam, there is a considerable chance that the Doppler radar speed meter is not registering the wanted target's speed. In fact, an equal-size two-target case was experimentally simulated. Doppler frequency due to target vehicle 1 of speed 20 mi/h was simulated by 628-Hz output from HP model 200CD wide-range oscillator, serial no. 229-44352. Speed of target vehicle 2 of 20, 40, 60, and 80 mi/h was simulated by another HP model 200CD wide-range oscillator, serial no. 229-44637. Both oscillators' outputs were carefully adjusted to be equal to simulate equal-size echoes from individual targets. The output from the two oscillators was combined in series and fed into a HP model 521C electronic counter, serial no. 2938. The experimental results are tabulated in Table I and compared with the theoretical results calculated from (30). As seen from this table, the theory agrees with the simulated experiment. The radar reading was not equal to the target vehicle's speed of either Target 1 or 2 except in one case where Target 1 and Target 2 traveled at the same speed of 20 mi/h. To reduce this kind of problem, one solution is to utilize a sharp and well-defined radar beam for high resolution. The use of millimeter waves or a laser can make high resolution possible with an antenna of reasonable size. For example, at a frequency of 50 GHz it is not difficult to make a beamwidth of 10 minutes of arc. This beam covers only 4.5 feet of width at 1500 feet. Therefore, it is useful for police radar for the determination of traffic speed. This high-resolution radar along with a camera that is attached to the radar to take a picture of the target when the speed was measured will reduce arguments in the court of traffic-speed violation. Raising the Doppler radar's carrier frequency means, from (3), the rise of Doppler frequency. Accurate frequency counters are commercially available up to 10 GHz. This means that it is possible to raise the carrier frequency up to 10^6 times the frequency of current practice. This indicates the feasibility of millimeter waves of laser Doppler radar for traffic-police application.

VI. Conclusion

Most Doppler radars currently used are satisfactory for speed measurement when only one target exists in the radar beam. When two or more targets appear in the radar beam, the speed meter will register the speed of one of them or the average speed of them or some other value. With the use of the gating circuit and clipper circuit, smaller targets can be eliminated to a certain extent [8], [19]. When the targets are comparable in size with different speeds, the meter reading will fluctuate. Theoretically it is uncertain that the speed meter indicates any one of the targets' speeds. There will be a fading effect if

TABLE I
SIMULATED TWO-TARGET EXPERIMENT

Simulated Target 2		Simulated Radar Reading: Theory		Simulated Radar Reading: Experiment	
Speed (mi/h)	Doppler Frequency (Hz)	Speed (mi/h)	Doppler Frequency (Hz)	Speed (mi/h)	Doppler Frequency (Hz)
20	(628)	20	(628)	20	(628)
40	(1256)	30	(942)	30	(942)
60	(1884)	40	(1256)	40	(1257)
80	(2512)	50	(1570)	50	(1571)

Simulated target 1, speed 20 mi/h (628 Hz).

they are traveling at the same speed. There is no theoretical assurance that the speed meter is registering the wanted target's speed when there are two or more targets with different speeds in the radar beamwidth with commonly used traffic-police Doppler radars. This theoretical conclusion is contradictory to the common belief that the radar registers the speed of the target with the highest speed when several targets are in the radar beam [8].

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