Mark E. Goodson,[1] *B.S., P.E.*

Technical Shortcomings of Doppler Traffic Radar

REFERENCE: Goodson, M. E., **"Technical Shortcomings of Doppler Traffic Radar,"** *Journal of Forensic Sciences,* JFSCA, Vol. 30, No. 4, Oct. 1985, pp. 1186-1193.

ABSTRACT: Doppler radar is widely accepted as a tool that can be used to decrease the prevalence of vehicle speeding. While Doppler radar is based upon scientific principles, it still suffers from very real problems that can lead to the arrest of innocent persons. The theory of operation of Doppler radar are explained, and the causes for errors in measurement are explained. Suggested improvements are listed that would help to eliminate many of the present inaccuracies in Doppler radar.

KEYWORDS: criminalistics, radar, driving (motor vehicle operation)

The Arab oil crisis of 1973 brought with it a nationally mandated 89-kph (55-mph) speed limit. Law enforcement officers began to rely more and more on the use of Doppler radar to help uphold this speed limit. The Doppler principle, formulated in the 1800s by Christian Doppler, is the basis for operation of traffic radar. The Doppler shift, often described by the "approaching train whistle pitch" effect, is not questioned; however, it has some problems when applied to vehicle speed measurement. When traffic radar is operated without respect to these problems, it is possible for innocent citizens to be falsely accused.

Theory of Operation

Doppler-based traffic radar consists of a microwave antenna/transceiver, signal processing circuitry, and a numeric display. A block diagram is shown in Fig. 1. The microwave frequency transmitted can be either 10.525 GHz (X-band) or 24.150 GHz (K-band). In use, the microwave signal is transmitted and reflected off of an approaching target vehicle, and then returns to the antenna. The frequency of the received signal will differ from the frequency transmitted. This difference in frequency is proportional to the velocity of the target vehicle. For X-band, 1.61 kph (1 mph) results in a Doppler frequency of 31.39 Hz; for K-band, the shift is 72.02 Hz for every mph the target is travelling. The antenna/transceiver mixes the transmitted and reflected signals and passes the difference signal to the signal-processing circuitry.

Signal-processing techniques vary among the radar manufacturers. Typically, the circuitry looks for a signal whose frequency is constant for a certain period of time. If $dF/dt = 0$, then the Doppler frequency is stable, and it is presumed that this frequency represents a valid target velocity. Should the Doppler-frequency fluctuate, the signal could be either noise or indicate reflections from multiple targets. In this second case, $dF/dt <> 0$. The radar unit will only

Received for publication 14 Dec. 1984; revised manuscript received 15 Feb. 1985; accepted for publication 5 March 1985.

[1]Principal, Goodson Engineering, Inc., Lewisville, TX.

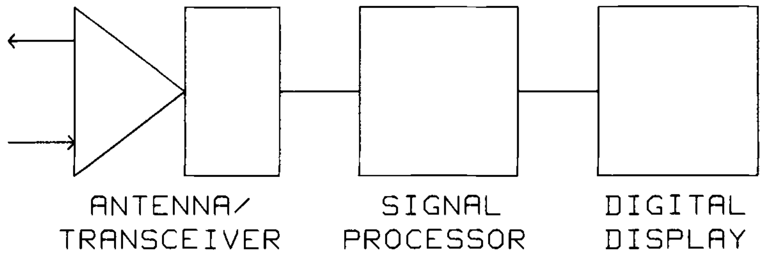

FIG. 1—*Traffic radar can be broken down into three basic building blocks: (1) the antenna/transceiver, which acquires the Doppler signal; (2) the signal processor, which validates the signal and converts it into mph units; and (3) the digital display, which provides a numeric readout.*

provide a display when it receives a signal whose frequency is time-invariant for a certain period of time (refer to Fig. 2). Should an X-band radar unit receive a constant Doppler frequency of 1569 Hz, it would display a reading of 80 kph (50 mph). A K-band radar would display 80 kph (50 mph) when the Doppler shift is 3600 Hz.

The above description applies to stationary radar. Stationary radar implies that the patrol vehicle does not move while the target is approaching the patrol vehicle. Moving radar, a more advanced type, allows the patrol vehicle to be moving while determining the speed of both the patrol vehicle and vehicles travelling in the opposite direction. Moving radar units have displays which show simultaneously the speed of both the patrol and oncoming target vehicles. Moving radar signal processing circuitry is different from that of stationary radar in that it must process two separate signals. The first signal is proportional to the ground speed of the patrol vehicle. It is the part of the transmitted radio waves that reflects off of both the ground and stationary objects. The second frequency is proportional to the closing speed of both the target and patrol vehicles. This second signal will always be higher in frequency than will the first signal. As an example, a patrol vehicle travelling at 72 kph (45 mph) would have a ground return signal of 1314 Hz. If a target vehicle was approaching at 89 kph (55 mph), the second frequency would be

$$(72 \text{ kph} + 89 \text{ kph}) \times 19.50 \text{ Hz/kph}$$
$$(45 \text{ mph} + 55 \text{ mph}) \times 31.39 \text{ Hz/mph}$$

or 3139 Hz. The signal processing circuitry would subtract 1413 Hz from 3139 Hz to obtain the Doppler frequency of the approaching car. This signal would have a frequency of 1726 Hz, which corresponds to 89 kph (55 mph). As with stationary radar, the signals are both checked to insure that they are stable in frequency.

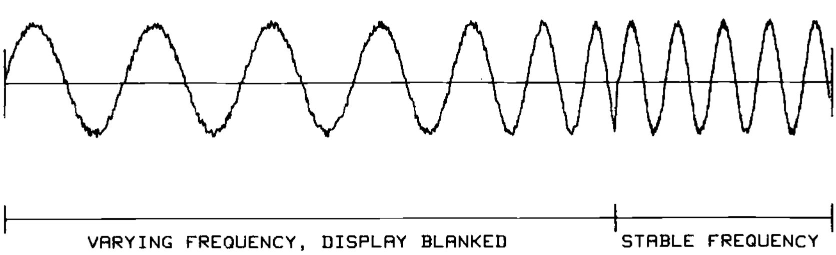

FIG. 2—*Traffic radar displays a numeric reading only when the Doppler frequency is invariant over time. In this example, a speed reading would not be obtained until the stable Doppler frequency was found.*

Errors with Doppler Radar

The first error associated with Doppler radar is referred to as "cosine error." Cosine error occurs when the velocity of the vehicle is in a different direction than the direction in which the radio wave is travelling. In Fig. 3, a vehicle whose velocity is 103 kph (64 mph) approaches a stationary patrol car. The microwave beam is at a 25° angle with respect to the oncoming car. The Doppler frequency will thus be

$$(103 \text{ kph } [64 \text{ mph}] \times 19.50 \text{ Hz/1 kph } [\text{mph}] \times \cos 25)$$

or 1820 Hz. This indicates a vehicle whose speed is 93 kph (58 mph), rather than the true velocity of 103 kph (64 mph). This stationary mode error will always favor the speeder.

In Fig. 4, a five-lane highway has a car travelling in each lane at 105 kph (65 mph). If the patrol car is 30.5 m (100 ft) away from each car before it is clocked (that is, when the patrol officer is hiding beyond a hilltop) the five cars will each have different observed speeds, ranging from

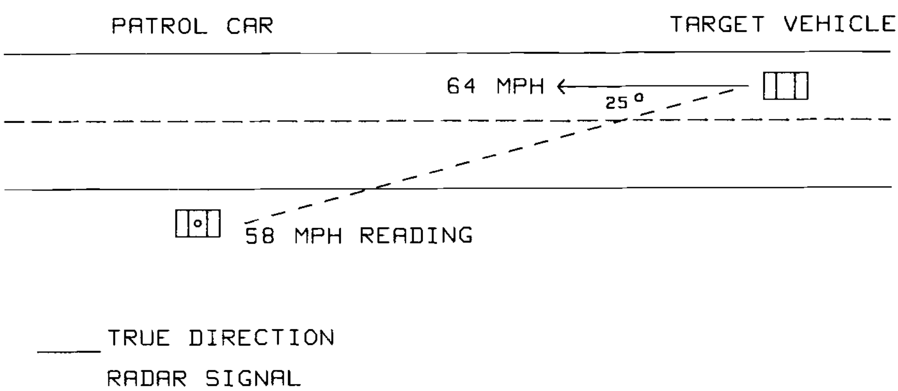

FIG. 3—*Because the target vehicle travels at a 25° angle with respect to the microwave beam, the true 103-kph (64-mph) speed is instead displayed as 93-kph (58-mph).*

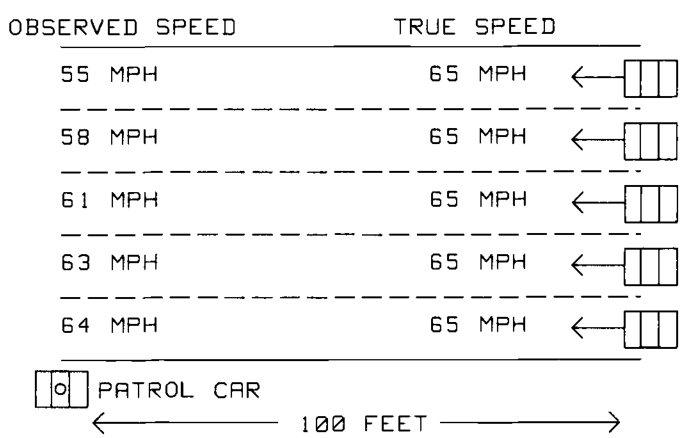

FIG. 4—*Five adjacent vehicles each approach a stationary patrol car 30.5 m (100 ft) away. Although each is travelling at a velocity of 105 kph (65 mph), the Doppler reading will vary from 103 kph (64 mph) down to 89 kph (55 mph) because of the cosine error.*

103 to 89 kph (64 to 55 mph). The tactical advantage an officer thus gains by hiding over hills or behind obstructions is thus partially cancelled due to the cosine error.

In moving mode, the cosine error can favor either the speeder or the patrol vehicle. It is the latter case which must be given attention. In Fig. 5, a target vehicle approaches a moving patrol vehicle. Both have speeds of 89 kph (55 mph). The target is of sufficient distance from the patrol vehicle so that cosine errors related to the 177 kph (110 mph) closing speed are avoided. However, the patrol vehicle passes a large, metallic billboard. The ground return signal is now small in amplitude compared to the reflection from the metallic billboard. The signal processing circuity will now process the return signal from the billboard. Because there is a large angle between the billboard and the patrol vehicle, the cosine error will cause the radar unit to understate the true velocity of the patrol vehicle. This causes the speed reading of the target vehicle to be higher than is correct. In this example, a 8 kph (5 mph) error in the speed of the patrol vehicle will cause the target vehicle's speed to be displayed as 97 kph (60 mph), rather than the correct 89 kph (55 mph).

A second problem inherent with both stationary and moving radar is caused by a change in frequency of the microwave oscillator. Radar manufacturers supply an external tuning fork for checking calibration of the radar unit, but this tuning fork only verifies the accuracy of the timebase that converts the Doppler frequency into a digital reading. The tuning fork does not insure that the microwave generator is of the correct frequency. The Doppler equation states that the Doppler difference is proportional to the transmitted frequency. If the transmitter produces a signal higher in frequency than 10.525 (X-band) or 24.150 GHz (K-band), the radar unit will read high; lower transmission frequencies result in lower speed readings. In either case, the error will not be detected by the tuning fork calibration check.

An additional calibration problem can be found on those radar units that use an internal mechanical tuning fork as the frequency reference. While most radar manufacturers use a quartz crystal, one manufacturer has chosen the mechanical reed technique. The author has found these mechanical reeds to be very temperamental, particularly on extremely hot or cold days. On such days, the radar unit will continually read the speeds of vehicles incorrectly until the internal operating temperature reaches a more moderate level. This type of error can be detected by using the manufacturer provided external tuning fork.

"Ghosting" refers to the tendency of radar units to display speed information when no target is visible. In the case *Florida v. Aguilar*, it was alleged that a radar unit had clocked the speed of a clump of trees. This is an example of ghosting. This phenomenon is caused by anything that can alter some of the microwave beam's characteristics. Patrol car radios, mobile

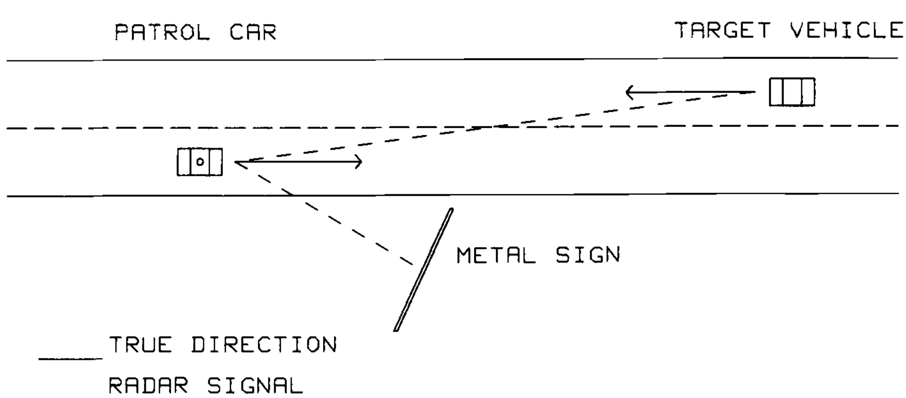

FIG. 5—*Moving mode cosine errors that overstate target vehicle speed occur whenever the patrol vehicle passes large reflective objects, such as signs. Any understatement of patrol car speed results in a higher-than-true target vehicle reading.*

telephones, and CB radios are good examples. When these radios transmit in close proximity to the radar unit, it is not uncommon for the unit to display false information. Heating and air conditioning fans inside the patrol car can also cause erroneous displays of information. A well-trained operator should recognize immediately a ghost reading, and not associate it with a target vehicle.

Perhaps the biggest problem associated with radar is its nonspecificity. It is often difficult to correlate a displayed reading with a particular target vehicle. The amount of energy reflected from a target vehicle is related to the cross-sectional (frontal) area of the vehicle. Larger targets can reflect more energy than do smaller vehicles, and thus will be detected at greater distances. In Fig. 6, a stationary patrol car clocks approaching traffic. At a distance of 610 m (2000 ft), a small car approaches the patrol car; at the same time, a tractor-trailer rig, 1220 m (4000 ft) away, also approaches. It is possible that the displayed reading will be that of the tractor-trailer rig. However, the operator will most likely associate the reading with the smaller, closer car. If the tractor-trailer is in violation of the law, the driver of the small car is subject to being cited, regardless of his true speed.

The second area of nonspecificity with radar is caused by the large beamwidth of the transmitted signal, usually 6 or 7°. At a distance of 610 m (2000 ft), the width of the beam can easily detect the speed of a vehicle in any one of ten or twelve lanes of a multi-lane highway. Multiple approaching targets then cause even more of a problem as the officer must now determine what vehicle is causing which speed reading. The radar manufacturers have helped to aggravate the problem by installing "gun sights" on tops of hand-held radar guns. In reality, the gun sights are made useless by the wide beamwidth of the antenna.

Another problem with radar is caused by the use of the "autolock" mode. On many radar units, the operator can dial in a desired trip point. A vehicle whose speed is greater than this will cause the radar unit to sound a warning tone and will also lock the displayed speed so that it will not disappear. As an example, the officer might set the switches to 105 kph (65 mph). Any speed reading exceeding 105 kph (65 mph) will cause the alarm to sound. While this is viewed as convenience by patrol officers, it actually casts doubt upon the displayed reading. The autolock feature allows the officer to operate the radar unit while paying little attention to either the traffic or the displayed readings. The officer is alerted only if an excessive speed is detected. By disabling the autolock function, the officer is required to correlate observed changes in vehicle velocities with changes in displayed readings. The author has found that there is a much greater degree of certainty with the autolock off. Conversely, the author has found that the use of the autolock destroys all tracking history of the observed vehicle's motion and the displayed readings.

The last problem is really a pair of problems, and they both deal with the agencies charged

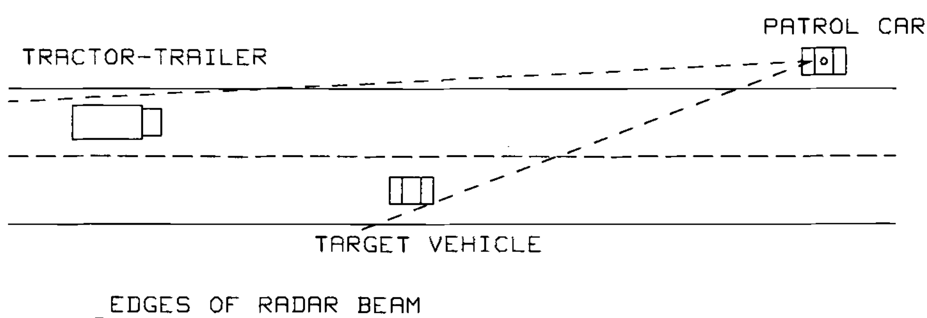

FIG. 6—*Because of the large frontal area of the approaching truck, its speed will be displayed even though the small car is closer to the patrol car. It is very likely that the patrol officer will associate the truck's displayed speed with the motion of the small car.*

with traffic enforcement. Many improvements have been made in traffic radar over the last several years. Yet many small jurisdictions have not updated their radar units. They still continue to use units which are obsolete. These older units are much more prone to false readings than are the newer ones; that is why they are no longer built by radar manufacturers. The second problem lies with the officer using the radar; if the officer is not motivated to use radar in a proper fashion, no amount of circuit improvements will aid in proper administration of justice.

Discussion

There are also other errors which might occur, but those presented are the most serious ones found by the author. The most likely error to occur is the cosine error. It favors the violator in the stationary mode, but can favor either vehicle in the moving radar mode. The moving mode error should be noticed by the experienced police officer; the displayed patrol car speed will not match that of the speedometer. It should also be noted that moving mode cosine error is affected by one of the basic laws of physics: the angle of incidence is equal to the angle of reflection. This helps maintain the reflected signals off of very close billboards and stationary objects at low amplitudes. Thus, moving mode cosine error does not occur as often as might be expected.

The radar manufacturers could improve upon this moving mode cosine error scenario by the use of Digital Signal Processing (DSP) techniques. Many of the radar units currently in use have two separate antennae, one pointing forward, the other aimed out of the rear window. However, only one is ever in use at one time. If both antennae were used at one time, DSP techniques could be used to compare the frequencies of both the front and rear antenna ground-speed signals. If the two were identical, there is a lessened chance of cosine error that would favor the patrol vehicle. If the two were different, the radar unit should blank its display temporarily, as there is some type of problem. DSP methods could also be used to obtain phase information; this could be used to determine the direction of target vehicles.

One manufacturer, rather than using DSP techniques, has chosen to use speedometer pick-off circuitry. In this way, the radar unit tracks both the Doppler return signal and the transmission speed. This is somewhat of an improvement, but speedometers are subject to error caused by tire pressure, temperature, tire tread depth, and surface traction. DSP techniques form a better long-term solution.

The stationary mode cosine error can also be used as a defense tactic during traffic litigation. The police officer is often asked a question by the prosecutor that is similar to this: "Officer Smith, you stated that the radar unit displayed a reading of 105 kph (65 mph). In your professional opinion, was that indeed the speed of the vehicle?" The officer will then answer in the affirmative. The defense attorney can then base his case upon the fact that the officer was sitting at a large angle with respect to the target. (Hiding beyond a hill and off to the side of the road is a good example.) Because the angle is so large, the radar understated the speed by a large percent. If the radar unit displayed 105 kph (65 mph) and the angle was 40°, the true speed must have been 137 kph (85 mph). The officer, however, has now made his testimony suspect by claiming that the vehicle was indeed travelling at a rate of 105 kph (65 mph).

Calibration errors are induced by equipment problems. The drift of the microwave oscillator is a rare occurrence, but the author does indeed have a radar unit that has that problem. The unit will pass tuning fork checks, but it still measures speed improperly. Any officer who stated that the radar unit is in calibration based on tuning fork checks is incorrect. To make matters worse, *State v. Tomanelli* [*1*] and *Honeycutt v. Commonwealth* [*2*] both support the theory that the tuning fork is a reliable means of checking calibration. The tuning fork does check one portion of the radar unit, but it cannot be used to verify microwave oscillator frequency. There is only one good method of checking the frequency of the oscillator, and patrol officers do not have the necessary equipment in their patrol cars to make this test. It would be possible, using state-of-the-art electronics, to design a calibration standard that could be carried in the patrol vehicle and which would indicate if the microwave source was out of tolerance.

The second calibration error is only found in the units which rely on an internal mechanical reed for a timebase. These units operate improperly when the temperatures inside the radar unit are quite warm or cold. A skilled officer should notice this problem; this error can be found using the manufacturer provided external tuning fork.

Ghosting is a problem that cannot be eliminated, but proper training of officer can help eliminate unwarranted arrests. If the operator carefully tracks the vehicle's motion and the displayed speed, a higher confidence factor can be realized, and the ghosting problem can be lessened.

The lack of target specificity is a shortcoming that could be lessened by better antenna design. The current radiation pattern of the antennae used can best be thought of as a poorly focused flashlight beam. By tightening the beamwidth of the radar unit, it would be possible to better associate a given reading with a particular vehicle. As an example, a 1.5° antenna will have a half-power radiation pattern 7.9 m (26 ft) wide at a distance of 305 m (1000 ft). With the current 7° antennae, the half-power pattern is 37 m (122 ft). Such an antenna would cost more, and the antenna design might require a parabolic shape, as opposed to the current conical horn. Yet it would be more accurate.

A better antenna design will not solve all of the target discrimination problems. The officer must still verify that the speed being displayed is that of the suspected vehicle, and not that of a more distant vehicle that has a large cross-sectional area. Some manufacturers use range controls to aid in this situation; however, range controls are of little aid. Large vehicles will always be detected at greater distances than will smaller vehicles.

The autolock feature is one item that should not be allowed as part of radar units. In use, the officer does not usually observe either the target vehicle or the radar display until a buzzer sounds. The speed is locked on the display, and it is not possible to obtain a good tracking history of displayed readings and vehicle motion. The autoclock allows the officer to be less attentive to his law enforcement duties, and this is certainly not desirable.

The problem of obsolete equipment could be dealt with easily by members of the judiciary. It would be a simple matter to dismiss all cases in which evidence was obtained by use of an obsolete radar unit. The federal government has issued specifications for radar units, DOT-HS-80-191. The prosecution should be required to produce a certificate of compliance for the radar unit in question. If it does not conform to these specifications, it would seem fair to dismiss the case.

The last problem, that of the unconscientious operator, is perhaps the most difficult to solve. The ultimate solution is for radar manufacturers to develop a product that will require no judgement calls on the part of the officer. A laser Doppler instrument that records all traffic movements and Doppler signals on videotape for later playback in court would be ideal. Until such equipment is developed, no amount of circuitry or antenna changes can prevent an unconscientious or over zealous officer from issuing tickets at will.

Summary

Many of the causes of inaccuracies in Doppler radar have been described. The above types of errors are certainly not the only ones that could occur, but they are the most common. The scientific reasons that radar traffic readings can be suspect have been shown, and several recommendations have been made that would improve upon the current situation. If these changes were made, and coupled with the mandatory removal of obsolete equipment, a fairer and more reliable traffic enforcement system would result.

References

[*1*] *State v. Tomanelli*, Conn., 216A2d 625.
[*2*] *Honeycutt v Commonwealth*, Ky., 408 SW2d 421.

Address requests for reprints or additional information to
Mark E. Goodson
Goodson Engineering, Inc.
1904 Sierra Dr.
Lewisville, TX 75067