Doppler-limited Microwave Motion Detection Zone

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November 23, 2019

Introduction

The Doppler effect upon which microwave motion sensors depend is zero for motion transverse to the line of position between the far field microwave radiation center and the target whose motion is to be detected.[1] If the motion of the target is linear – that is, if it follows a straight line – there is only one point along the trajectory of the target at which motion is transverse and at which the Doppler effect is, consequently, zero. Namely, at the point along the trajectory that is closest to the radiation center. The Doppler effect increases monotonically in either direction along the trajectory for points progressively further from the zero Doppler point.

All microwave motion sensors exhibit a minimum speed below which they are unable to detect motion. This is a consequence of the fact that there is a minimum Doppler frequency below which such sensors are unable to detect motion. For the linear motion of the target to be detected, the target must be moving sufficiently far from the zero Doppler point for the Doppler frequency to have reached the detection threshold exhibited by the sensor. Put another way, the ***relative*** motion between the motion sensor and the target must have reached the threshold speed of detection characteristic of the sensor.

There is, generally, a point along the trajectory short of the zero Doppler point at which the Doppler effect drops below the minimum required by the sensor, and, likewise, there is a second point beyond the zero Doppler point at which the Doppler effect

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[1] Given the typical radiator size and the current use of k-band (24.125 GHz) microwaves, the transition to the far field occurs approximately 2.5 inches from the sensor. Consequently, users of automatic pedestrian doors with microwave motion sensors do so well within the far field of the sensor.

increases above the minimum required by the sensor.[2] The purpose of this paper is to derive an expression for the distance from the zero Doppler point on a linear trajectory within which the Doppler effect remains below the speed threshold of detection of a microwave motion sensor. The specific instance used in the derivation is that of linear horizontal motion directly beneath a microwave motion sensor mounted on the header of a door. However, the principle applies as well to linear motion in any location and in any direction relative to the sensor.

Derivation

Figure 1 below defines the relevant parameters used in the derivation. h is the height of the horizontal trajectory above the floor. d is the distance from the far field microwave radiation center to the closest point along the trajectory **A**. z is the height of the radiation center above the floor. x is the distance along the trajectory from the zero Doppler point **A** to the point at which the Doppler effect transitions to the threshold of detection characteristic of the sensor, and r is the relative distance between the radiation center and the target at the transition point.

It is clear from **Figure 1** that

$$d = z - h \,. \tag{1}$$

Since the heights of the sensor, z, and of the target trajectory, h, are constant, the distance d is also a constant. It is also clear from **Figure 1** that, according to the Pythagorean Theorem,

$$r^2 = x^2 + d^2 \,. \tag{2}$$

Since the Doppler effect occurs only when the relative distance r changes, it is necessary to determine the rate of change of r as a function of position x along the trajectory. This can be accomplished by taking the derivative of (2) with respect to time t. Because d is constant, the result is

$$2r\frac{dr}{dt} = 2x\frac{dx}{dt} \,. \tag{3}$$

Defining the speeds

$$\frac{dr}{dt} = v_r \quad \text{and} \quad \frac{dx}{dt} = v_x \,, \tag{4}$$

[2] The exception is if the speed of the target along its trajectory is below the speed threshold of detection of the sensor.

equation (3) can be solved for x as

$$x = r\frac{v_r}{v_x} = \sqrt{x^2 + d^2}\,\frac{v_r}{v_x} \tag{5}$$

where (2) has also been used in (5). v_x is the speed of the target along the trajectory

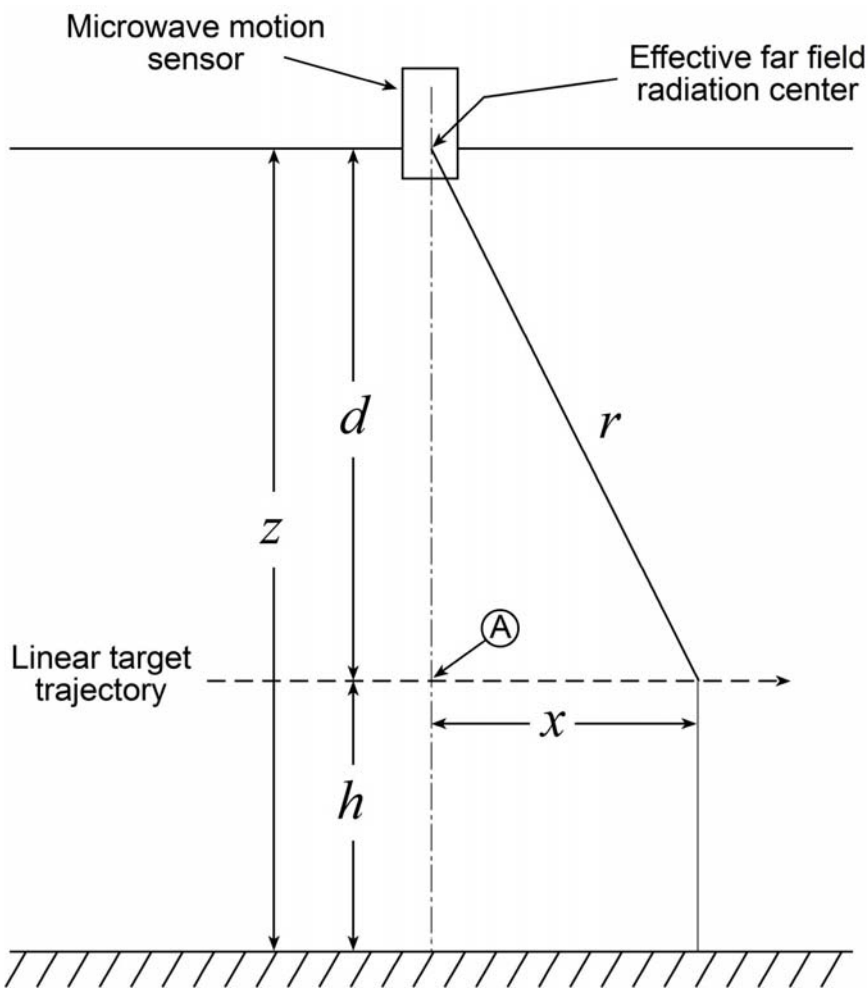

Figure 1. Relevant parameters in derivation of Doppler effect transition point along a horizontal linear trajectory.

and v_r is the speed of the target relative to the sensor. It is v_r that must equal or exceed the speed threshold of detection of the sensor for the motion of the target to be detected.

Squaring both sides of (5) gives

$$x^2 = x^2\left(\frac{v_r}{v_x}\right)^2 + d^2\left(\frac{v_r}{v_x}\right)^2$$

from which

$$x = d\,\frac{v_r/v_x}{\sqrt{1-(v_r/v_x)^2}}\,. \tag{6}$$

Equation (6) expresses the relationship between the rate of change of the distance of the target from the sensor, v_r, and the instantaneous location of the target along its trajectory, x. When the target is at the location at which v_r is equal to the speed threshold of detection of the sensor, v_s, the distance x from the zero Doppler point on the trajectory is x_s where

$$\boxed{x_s = d\,\frac{v_s/v_x}{\sqrt{1-(v_s/v_x)^2}}} \tag{7}$$

As an example of the use of this equation, consider a horizontal trajectory 28 inches above the floor, that the target is moving at a speed of 6 inches/second along the trajectory and that the speed threshold of detection of the sensor is 2 inches/second. Assume that the center of microwave radiation is 83 inches above the floor. Using also (1), the numerical parameter values entering (7) are

$$\text{with } h = 28,\ z = 83 \ \Rightarrow\ d = 55,\ \ v_s = 2\,,\ \ v_x = 6$$

from which the dimensionless constant multiplying d in (7) has the value

$$\rho \equiv \frac{v_s/v_x}{\sqrt{1-(v_s/v_x)^2}} = 0.354 \tag{8}$$

so that

$$x_s = d\rho = 19.45 \text{ inches.}$$

Thus, under the specified conditions, there are 19.45 inches on either side of the zero Doppler point on the trajectory, or a total of 38.9 inches of the trajectory, along which the Doppler effect lies below the speed threshold of motion detection of the overhead sensor.

Graphical Calculation

Given the dimensionless factor appearing in (7),

$$\rho = \frac{v_s/v_x}{\sqrt{1-(v_s/v_x)^2}}, \tag{9}$$

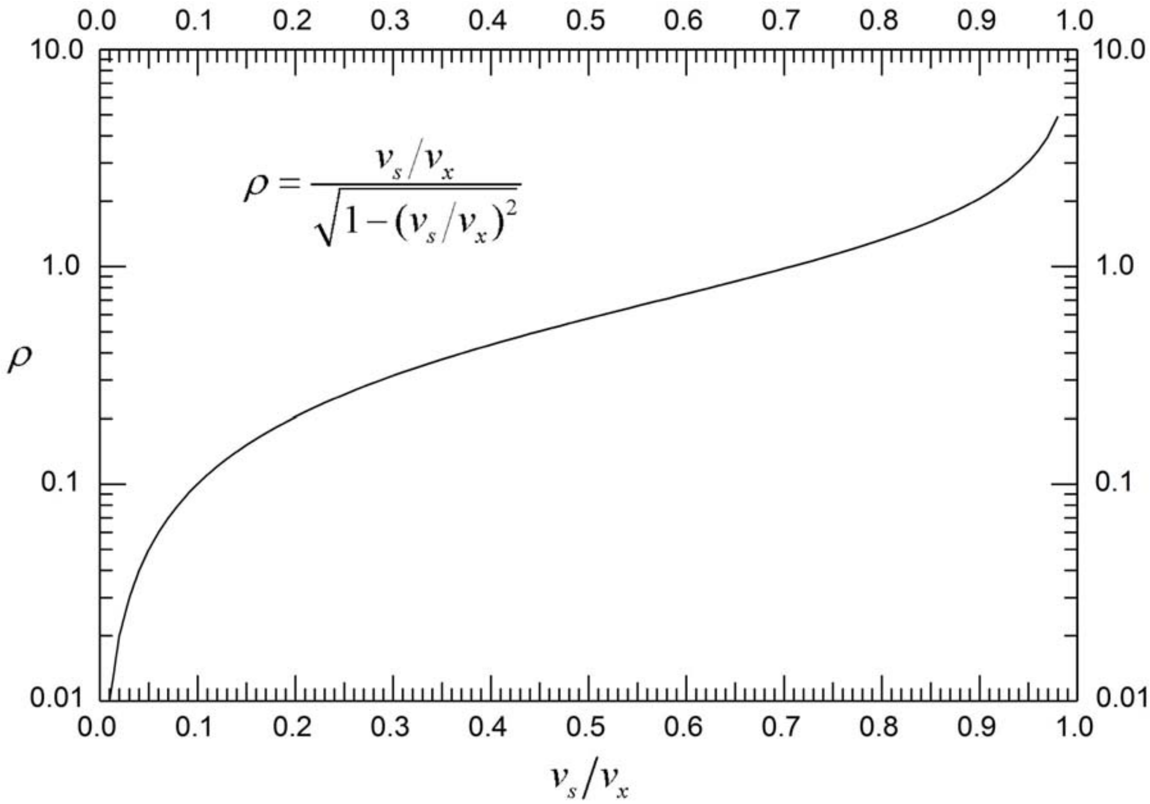

Figure 2. Graphical representation of dimensionless ratio ρ.

the transition point x_s along the trajectory is given by

$$x_s = (z-h)\,\rho = d\,\rho \tag{10}$$

where d is the distance of the closest point along the trajectory from the center of radiation within the motion sensor. **Figure 2** above is a graphical representation of (9) for a range of values of the dimensionless ratio v_s/v_x.

To compute x_s, locate the ratio v_s/v_x along the horizontal axis in **Figure 2**. Then, read off the value of ρ from the vertical axis. Finally, multiply ρ by d, given by (1), to obtain x_s.

Implication for Compliance with ANSI Standard

The relevant ANSI standards for automatic pedestrian doors specify parameters that sensors used to detect the motion of users approaching and moving in the vicinity of the door must meet. **Figure 3** below illustrates, to scale, the minimum motion detection zone permitted by ANSI A156.10 for automatic sliding doors. This includes the width of the motion detection zone at 8 inches and 30 inches from the face of the door and the minimum distal limit of 43 inches along the centerline through the door opening as illustrated in **Figure 3** below. Also illustrated on **Figure 3** are the regions within which the Doppler effect falls below the minimum threshold of detection for a horizontally moving target 28 inches above the floor moving at 6 inches per second beneath a microwave motion sensor. The center of microwave radiation is assumed to be 83 inches above the floor and radii of the minimum speed threshold contours were calculated using (7), and have the following values

Det. Threshold	Contour Radius
2"/sec	19.45"
3"/sec	31.75"
4"/sec	49.19"
5"/sec	82.92"

Although the minimum motion detection zone mandated by the ANSI standard extends to within 5 inches of the face of the door on the centerline through the door opening and to within 8 inches of the face of the door at the extreme right and left sides of the usable door opening, the motion of the 28 inch high horizontally moving target will not be detected within the respective contours due to the failure of the Doppler effect within the respective contour to reach the specified minimum assumed for the overhead microwave sensor. Even when the sensor is capable of detecting motion **relative to the sensor** of 2 inches/second, the radius of the area beneath the sensor in which this threshold is not met for a 28 inch high target moving horizontally at 6 inches per second is 19.45 inches, and, consequently, the sensor fails to comply with the ANSI standard, which requires detection of a 28 inch high object moving at 6 inches/second within the shaded area shown in **Figure 3**.

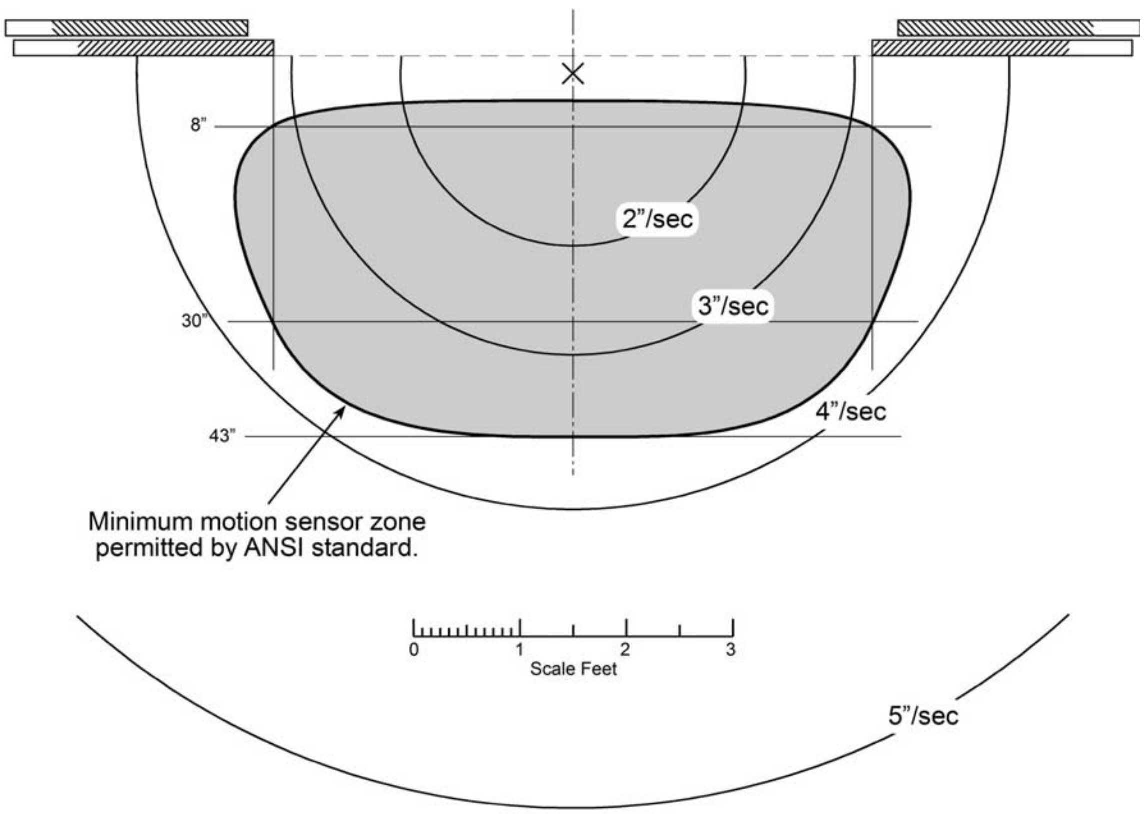

Figure 3. Minimum motion detection zone permitted by ANSI standard for sliding doors, with regions in which the Doppler effect for horizontal motion falls below the detection threshold of a microwave motion sensor.

It has been argued that, as a practical matter, a 28 inch high person moving within the shaded area in **Figure 3** will not be moving perfectly horizontally and, in particular, will be swinging arms and lifting and planting feet, and that these upward and downward motions will nevertheless result in detection. Unfortunately, this mechanism cannot be relied upon to produce detection.

A principal consideration is that the strength of the microwaves reflected from parts of the body below the head decreases as the fourth power of distance from the sensor due to the so-called radar equation. This means that the dominant reflection received by the sensor will be from the nearest part of the body, the head. Lower amplitude reflections from body parts below the head may be swamped by the stronger reflection from the head so that the weaker reflections may not produce the hoped for detection, though they might result in detection were it not for the overriding strong signal. Filtering out the stronger, lower frequency Doppler signal to permit detection of weaker, higher frequency components only increases the speed threshold of detection. As can be seen from **Figure 3**, this is counterproductive as it strongly increases the radius of the area of insufficient Doppler effect.

The Beam Edge Problem

The discussion above deals only with the Doppler effect, independent of the strength of the microwave beam at the point in space where the Doppler effect occurs. In fact, microwave motion sensors exhibit two distinct, mutually exclusive thresholds. The first is the Doppler effect frequency below which the sensor is unable to detect motion regardless of signal strength. The second is the minimum signal strength required by the sensor to produce detection regardless of the Doppler frequency of the signal.

The contour bounding the shaded area in **Figure 3** illustrating the minimum motion detection zone permitted by the ANSI standard conveys the mistaken impression that the edge of the zone is distinct and sharp to the extent that an object or person, or part of an object or person, is either within or without the zone. And, correspondingly, that detection will occur with certainty if any part of the object or person intersects the shaded area and is moving sufficiently rapidly.

Unfortunately, the crisp representation of the motion detection zone grossly misrepresents the true nature of the limits of the zone and its consequences.

In fact, the microwave signal strength tapers off ever so gradually from the center of the beam where it is strongest. Contrary to the impression created by **Figure 3**, the beam does not have a relatively constant amplitude for angles away from the center of the beam and then a sharp cut off delineating the outer edge, or surface, of the beam. Rather, the edge of the beam, which is represented so sharply and distinctly in **Figure 3**, is actually defined as the locus of points at which the beam strength has faded so precipitously that detection is no longer possible, entirely independently of the frequency of the Doppler signal that might otherwise be present if the signal strength were sufficient.

Motion detection is not reliable at the "edge" of the beam because the beam edge is so "soft". Being by definition at the very limit of useful signal strength, a slight further decline of strength at the edge, which would otherwise have no impact on detection, results in loss of detection. Moreover, a person walking toward the door is moving **away from** the beam and **not into** the beam where signal strength is high and detection is correspondingly reliable.

Clearly, motion detection immediately adjacent to the door would be made more reliable if the area of insufficient Doppler effect and the soft edge of the microwave beam were moved away from their current location close to the door.

Circumventing the Problem

The most obvious way to avoid the twin problems of insufficient Doppler effect and the soft beam edge in the area beneath the microwave sensor immediately adjacent to the door is to turn to another technology for motion detection. One such method is digital video image processing. Here real time video is analyzed to detect people and objects moving in the vicinity of the door. This method has the advantage that nothing is projected from the sensor – such as microwaves, infrared light or ultrasound – out into the environment to probe it via reflections back into the sensor. Consequently, the physics of interactions (reflections) over which the sensor has no control are avoided. Only ordinary visible light is required, the same phenomenon used by our eyes.

On the other hand, it is nevertheless possible to employ microwaves for motion detection in such a way that both the beam edge and the area of insufficient Doppler effect are moved away from the door so that reliable motion detection results in the area where it is most needed, within and adjacent to the door opening. The method is to use radar signature analysis within the sensor to record the Doppler signal of the door as it opens and closes in the absence of other moving objects, such as people. Then, when users approach the door, generating a Doppler signal, the recorded signal characteristic of the door opening and/or closing is subtracted from the incoming Doppler signal, leaving a residual Doppler signal encoding both the presence and the motion of the person in the vicinity of the door, but not the door.

In this way, the motion sensor can be moved away from the door, which likewise removes the area of insufficient Doppler effect and the beam edge, away from the door. Instead of the current arrangement, the microwave beam is aimed directly into the door opening providing both reliable signal strength and reliable Doppler effect within and near the door opening.[3]

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[3] See U.S. patent number 5,481,266 for additional details.