Fundamentals Of Commercial Doppler Systems

Speed, Motion and Distance Measurements

I. Introduction

MDT manufactures a large variety of microwave oscillators, transceivers, and other components for the motion-detection market.

These components have been designed for use in microwave systems that measure vehicle speed — (police radar and true ground speed for agricultural vehicles), detect motion (intrusion alarms), and measure range (braking systems) or direction of motion (stereo systems). The microwave Doppler sensors are also used in industrial control applications, such as counting objects moving on a conveyor belt, measuring vibration in machine parts or measuring levels of liquid products, etc. Another major use is for automatic door openers for public buildings.

The following Sections (II–VII) discuss some of the most important considerations when designing a commercial Doppler radar system.

II. Principles of Doppler Radar

When microwave energy is reflected by a moving target, there is a shift in frequency. All Doppler radars utilize this principle. The amount of frequency shift is directly proportional to the target's velocity relative to the radar's transmitter. A similar effect at audible frequencies occurs when an automobile horn is moving with respect to a stationary observer. The sound pitch is higher when the horn is moving toward the observer and decreases as it moves away from him. Figure 1 snows the situation of a target vehicle approaching a Doppler radar. The Doppler shift frequency (F_D) is given by:

$$F_D = 2V\frac{(F_0)}{C}\cos\varnothing$$

where

F_0 = transmitter frequency in hertz

C = velocity of light (3×10^8 meters per second)

V = velocity of the target (meters per second)

$\varnothing$ = angle between microwave beam and target's path

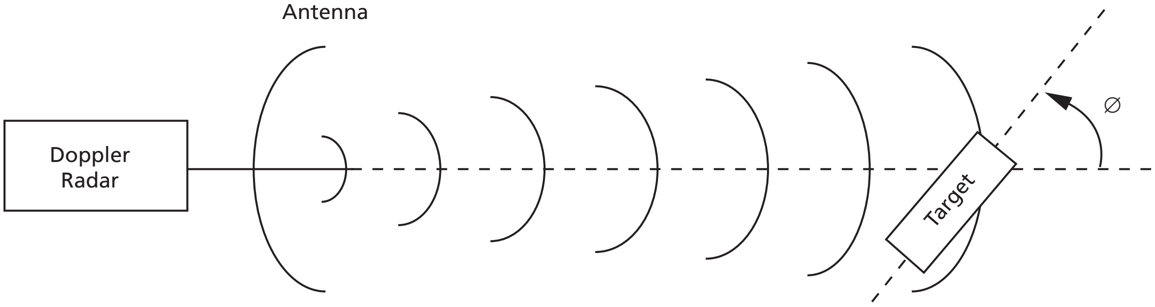

Figure 1. Doppler Shift Caused by Relative Motion of the Target

If ∅ = 90 degrees (target moving perpendicular to microwave beam) $F_D = 0$, there is no Doppler shift, i.e.,

If ∅ – 0 degrees (target moving parallel to microwave beam), $F_D = 2\ V\ (F_O/C)$, which gives the maximum Doppler shift attainable. Most police radars are used at an angle of ~15° (or less) when measuring automobile speed. The error is small and normally corrected in the software of a high-quality police radar.

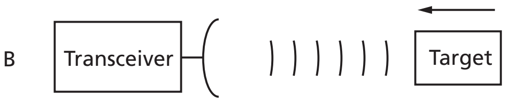

Figure 2 is a chart showing Doppler shift frequency (F_D vs. velocity (v)) for 10.525, 24.150 and 34.3 GHz. These are the usual frequencies used for police radars.

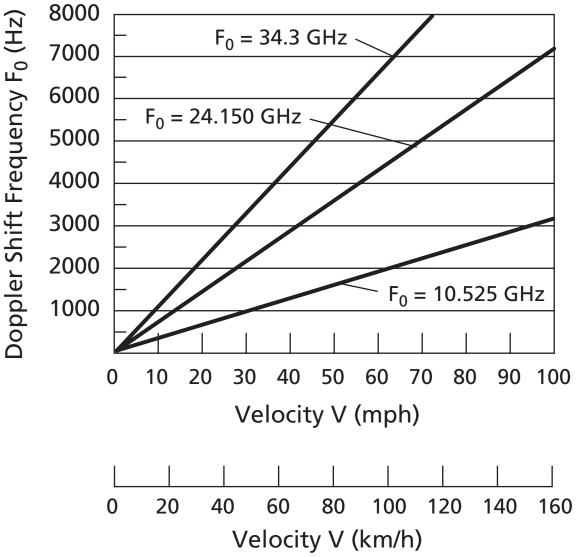

Figure 2. Doppler Frequency vs. Relative Speed of the Target

III. Typical Doppler Radar Systems

A typical Doppler radar is represented by the block diagram in Figure 3. This system consists of an RF (i.e., microwave) section, a signal processing section, and a well regulated power supply.

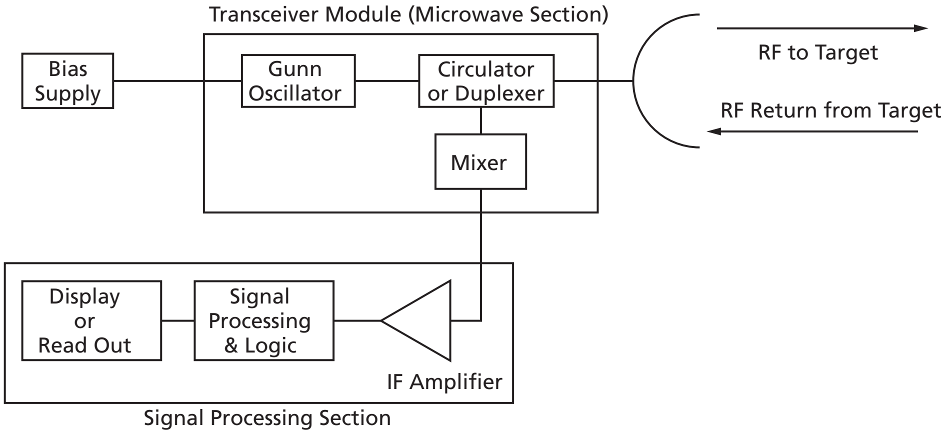

Figure 3. Typical Doppler Radar (Motion Detectors)

In order to design a Doppler radar system, one must first know:

1. The maximum range at which a target is to be detected (This determines the overall sensitivity and transmitter power required for the transceiver. It may also influence the antenna gain required.)
2. The maximum and minimum target speeds that the system is to measure (This determines the characteristics of the amplifier and its bandpass filter.)
3. The nominal radar cross section of the "target" one wishes to "observe".
4. Other environmental factors such as rain, fog or dust.

Note: These requirements are discussed in later sections. Doppler systems for police radars, intrusion alarms and most other applications usually operate with a "Zero IF". Some of the transmitter's power (Gunn Oscillator) is used as the local oscillator for the mixer. When using this technique, signal amplification occurs at the Doppler Shift Frequency.

For example, with the transmitter frequency 10.525 GHz, a vehicle traveling 50 mph causes a Doppler shift of 1568 Hz, which will be the IF frequency. This IF voltage is usually only a few microvolts RMS. at the mixer port in normal usage.

The IF amplifier's bandpass frequency for an X band police radar might allow 500–5000 Hz to pass, to include the range of target speeds expected, i.e., ~15 to ~150 mph. Police radars at K or Ka band will have higher IF frequencies (see Figure 2). The maximum target range of one mile is typical for a speed radar on a long, straight, flat road, although most are used at shorter ranges.

IV. Distance Measurement

A Stationary Target

The distance or range of a stationary target may be determined by changing the frequency of the transmitted signal during the "radar pulse" at a linear and known rate, and then comparing the frequency of the return to the transmitted signal. This can be done with a simple VCO transceiver, i.e.,

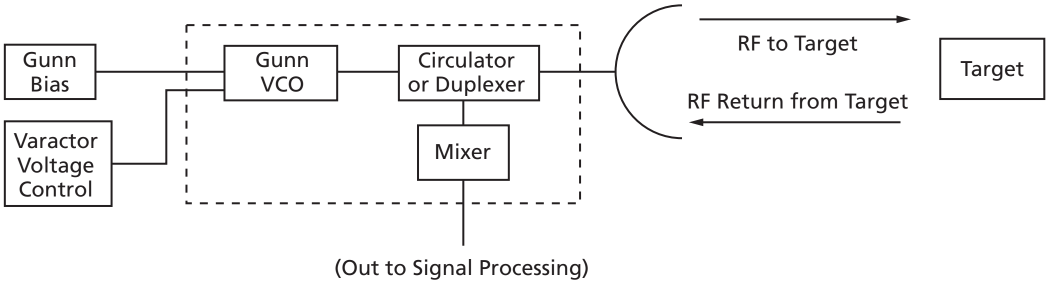

Figure 4. Voltage Controlled Transceiver

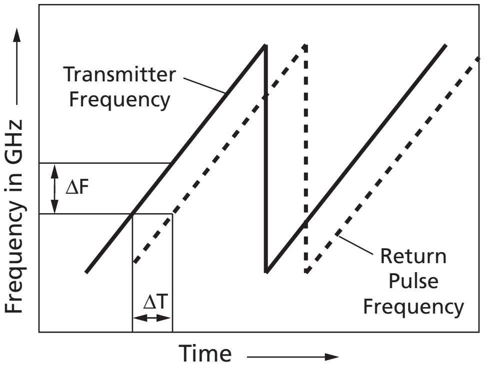

Figure 5. Gunn Voltage Controlled Oscillator Frequency vs. Time

The return signal will be shifted in frequency with respect to the initial signal transmitted. This shift (Δf) will be directly related to the amount of (ΔT) time it takes for the signal to make the round trip. We call this quantity the “transit time”. The transit time (T) is approximately 1 microsecond for a target 150 meters away (~500 feet). (microwave propagation occurs at the speed of light — approximately 1 nanosecond per foot).

The range of a stationary target can then be calculated by determining the transit time of the radar signal to and from the target, and multiplying that by the speed of light (see Equation 2). The transit time in seconds is given by the absolute value of the difference in the transmitted and return signal, i.e.,

$$(1)\ T = \frac{(F_T - F_R)}{K}$$

where
F_T = transmitter frequency in Hz
F_R = return frequency in Hz
K = rate of frequency modulation of the transmitter in Hz/sec
Note: $(F_T - F_R)$ is the IF frequency observed at the mixer’s IF port.

Then: The range is given by

$$(2)\ R = \frac{T \times C}{2}$$

where
C = speed of light in meters/sec = 3×10^8 meters/sec
T = transit time from (1) (in seconds)
R = range (in meters)

V. Direction-Sensing (Motion Detectors, Stereo) Systems

It is often very useful to be able to determine the direction of the target when using a motion detector such as an intrusion alarm or door opener.

A direction-sensing system can gate out vibrations or distinguish between approaching and receding targets. This can minimize false alarm problems caused by a vibrating surface such as a curtain blown by the wind. Energy can be conserved by quickly closing the door behind someone. Other types of background noise which can be removed are vibration of windows, moving fan blades, or incandescent light reflections.

A Doppler radar can give a target directional information by adding a second microwave mixer diode that is offset approximately 45° from the first mixer (at both the transmitted and received frequency). (See Figures 6a & 6b). The output of the 2 mixers is then fed to a phase comparator which measures the phase angle between the two detected signals.

If the target is approaching the radar, the first mixer will lead the second (see Figure 6a) i.e., the phase shift will be positive.

If the target is moving away, the first mixer will lag behind the second.

Vibrating targets, such as curtains or fans, will have periodic phase changes and can be cancelled. Incandescent lights give a periodic reflection too. This can also be determined and removed by software or a notch filter.

A stereo system can also measure velocity by determining the Doppler shift frequency in either IF Port. In a properly designed system, the Doppler frequencies will be equal.

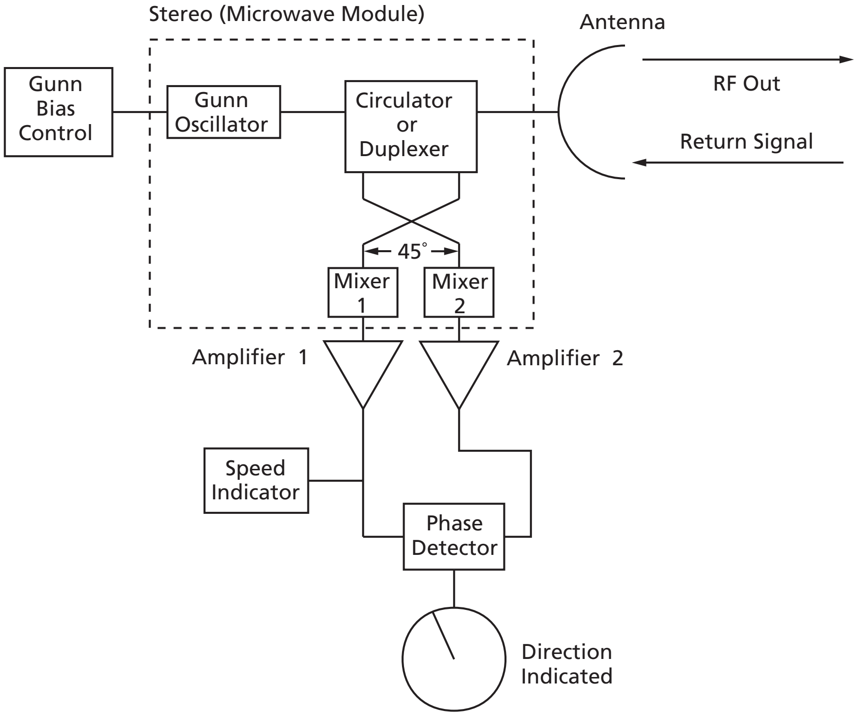

Figure 6a. Direction Sensing or Stereo Transceiver

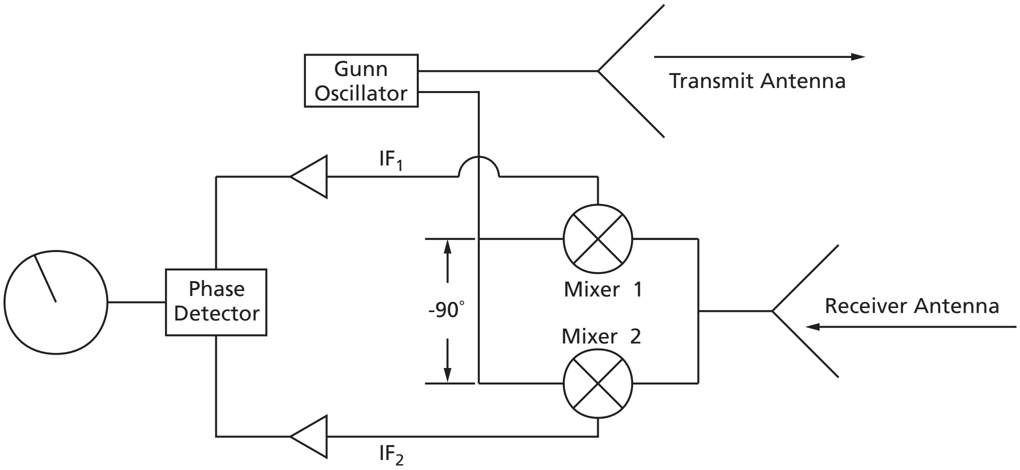

Figure 6b. Alternate Design Stereo Transceivers

VI. Range Considerations

The effective range of a Doppler system is a function of how much energy is reflected back to the transceiver from the target, and how strong that signal must be to make the receiver work properly. The major items controlling range are: 1) the transceiver's sensitivity, 2) the power output, 3) the gain of the antenna, 4) the reflection coefficient of the target and 5) the transmission or propagation loss.

When designing or using a motion detection system, the transceiver's sensitivity will be the single most important determinant of maximum range. Section VII discusses several factors that affect the receiver's sensitivity.

A second factor is the FM noise close to the carrier from its Gunn source. This can be best controlled by Gunn diode selection and proper Gunn bias conditions. MDT takes particular care to manufacture, characterize and select low-FM noise Gunn diodes for its transceivers.

Range can also be increased by increasing transmitter power — but doubling the transmitted power will only increase range up to 25% maximum. In many cases, we find that ground clutter (unwanted reflections) can result in very little practical increase in range.

The antenna gain affects the range too. In many applications, the beam shape of the antenna is more critical for proper operation than that of the gain it adds to the system. Beam shapes are usually chosen to fit particular applications. For example, a door opener placed over a door with a long, narrow entrance will require a different beam pattern than the same door opener placed in a building entrance which can be approached from both the side and the front. When a transceiver is used in a microwave barrier or fence (perimeter protection), a very thin, focused beam is required. This requires a vertical, high-gain antenna. Other custom-made antennas with different beam widths, antenna patterns and/or gains can be designed for specific requirements. All will affect range.

VII. Receiver Considerations

The characteristics and sensitivity of the receiver are normally the dominant factors in determining the range of a simple Doppler radar. Almost all commercial Doppler transceivers use low- or medium-barrier Schottky diodes for the detector/mixer. At normal L.O. bias levels, these diodes will have conversion losses of 5–8 dB (loss of return signal in the diode's mixing process).

All mixer diodes also have 1/f noise. This 1/f noise is an excess noise caused by surface states and traps in the semiconductor diode's material. The effect of 1/f noise is to increase the noise contribution of the diode as the IF or Doppler frequency is decreased. This noise increases with the reciprocal of the IF frequency, hence, the name (1/f noise).

The 1/f noise normally increases rapidly at IF frequencies below 100 KHz maximum and becomes the determinant factor in receiver sensitivity at low IF or Doppler frequencies, i.e., 10–5000 Hz as in intrusion alarms). Gunn diodes also have 1/f noise, but normally their noise contribution is much less than that of the mixer diode. This is a major reason to use higher frequencies, i.e., K or Ka band (police radars). The resultant IF Doppler frequencies are higher (see Figure 2) and the radars can be more sensitive (due to less 1/f noise).

The minimum sensitivity of the mixer diode can usually be improved by optimizing the L.O. drive (coupling of the transmitter) such that the diode's rectified current is small. (This may increase conversion loss slightly but can decrease 1 /f noise more, resulting in better signal-noise characteristics.)

In most cases, the best receiver sensitivity will be obtained when the mixer diode's rectified current is approximately 0.2–0.5 ma. We suggest using a 500–1000 Ω resistor for the diode's DC return. The detected voltage across the resistor should be approximately 0.2–0.5 V (DC). MDT's transceivers are normally factory-set for negative voltage.

It is very important that the bias resistor be a low-noise resistor. We suggest metal thin film resistors. Carbon composition resistors are not usually acceptable because their noise is too high and will degrade system sensitivity.

When the radar is detecting a target, the Doppler IF voltage from the mixer diode can be as small as 1 microvolt RMS (at the minimum system sensitivity) to ~10–100 millivolts (at the mixer's saturation). The IF amplifier (operational amplifier) must have enough gain to increase the voltage to that which is required for signal processing.

The operational amplifier should be chosen to have the lowest input noise possible, because this noise will decrease system sensitivity.

In general, the noise contribution of the amplifier should be less than 200 nanovolts RMS. (referenced to its input). This should be determined when the amplifier's input is loaded with a 500–1000 Ω resistor. It is also good practice to use a bandpass filter in front of the amplifier to restrict its bandwidth to that which is necessary for system operation. The amplifier's noise output increases with the square root of its bandwidth.