Doppler Effect and How it is Used in Measuring Speed

SM5013: Autonomous Navigation

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Doppler’s Effect: -

Christian Doppler (1842) was the first to measure effect of waves motion by help of group of musicians playing on an open moving railroad car along the track. He then applied his learnings to all waves (sound, light etc) and noted that if a source is coming close then waves are crowded and going far from the observer, the waves will be more spread out. This principle is now known as the Doppler effect, is illustrated in Figure 1

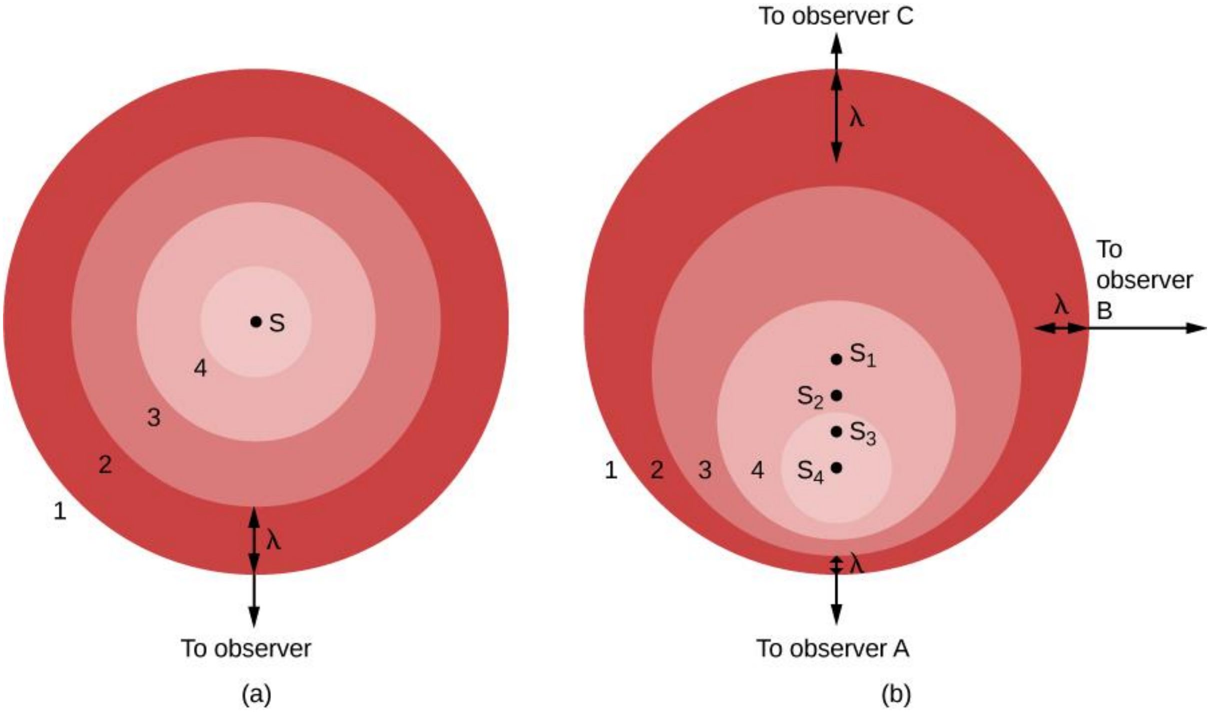


Figure 1: Doppler Effect. (a) A source, S, makes waves crests (1, 2, 3, and 4) wash over a relatively stationary observer. (b) The source, S, now moves toward observer A and away from observer C. Wave crest 1 was emitted when the source was at position S4, crest 2 at position S2, and so forth.

https://phys.libretexts.org/@api/deki/files/3809/OSC_Astro_05_06_Doppler.jpg

In Figure 1(a), the source (S) is at rest with respect to the observer. The source produce series of waves, whose crests are labelled 1, 2, 3, and 4. The waves spread out evenly in all directions. The crests are separated by a distance, λ (wavelength). The observer, who is present in the direction of the bottom of the image, observes the waves coming nice and evenly, one wavelength apart. Observers located anywhere else would see the same thing.

If the source is moving with respect to the observer, as shown in Figure 1(b), The time between crest 1 is emitted and the next one is ready to come out, the source has moved a bit, toward the bottom, towards observer A, this motion of the source has decreased the distance between crests.

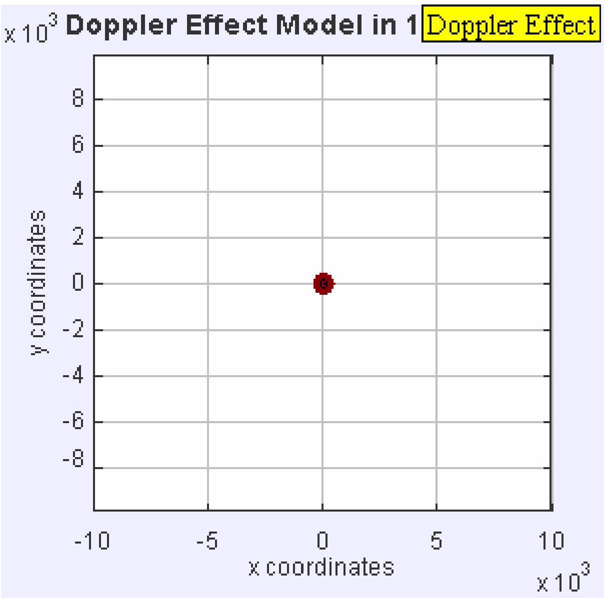
In Figure 1(b), We see the same source at 4 different positions S1, S2, S3, S4 with respect to 3 different perspective A, B, C. To observer A, the waves seem to be very close, at a decreased wavelength and thus increased frequency (as frequency is inversely related to wavelength).

For observer *C*, located opposite observer *A* in Figure 1(b). The source is moving away from him. As a result, the waves are spread out by the motion of the source. The crests arrive with an increased wavelength and decreased frequency.

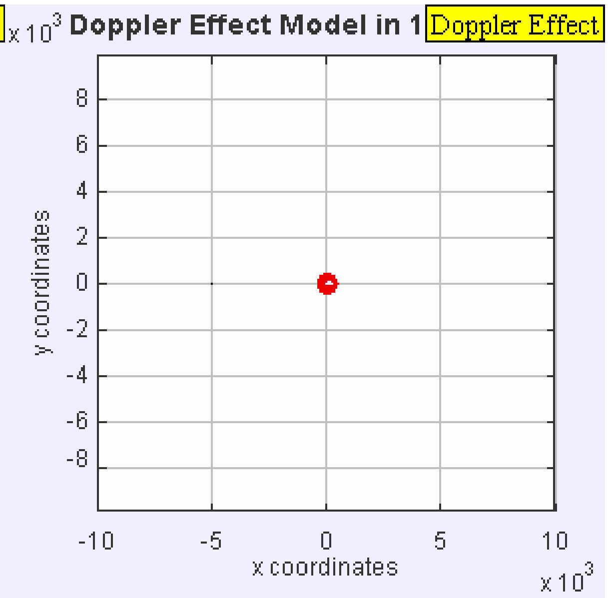
For observer B, who is at right angles to the motion of the source, no effect is observed. The wavelength and frequency remain almost the same as they were in part (a) of the figure.

From this we can see that the Doppler effect is produced only with a motion toward or away from the observer, a motion called radial velocity. Sideways motion does not produce such an effect.

The dopplers effect can be visually seen below



Stationary sound source produces sound waves at a constant frequency f



Moving sound source produces sound waves at a constant frequency f, but for observers on right and left, the frequency increase and decrease, respectively.

https://en.wikipedia.org/wiki/File:Dopplereffectstationary.gif

The Formula for Calculating Velocity with help of dopplers effect can be derived as-

- *This derivation is for moving source and stationary observer*

  Wave velocity,

$$c = \frac{\lambda_s}{T} \longrightarrow T = \frac{\lambda_s}{c}$$

  Distance can be written as,

$$d = v_s T$$

  Replacing Time T,

$$d = \frac{v_s \lambda_s}{c}$$

  Observer wavelength is given as,

$$\lambda_0 = \lambda_s - d$$

  Replacing d as,

$$\lambda_0 = \lambda_s \left(1 - \frac{v_s}{c}\right)$$

$$\lambda_0 = \lambda_s \left(\frac{c - v_s}{c}\right)$$

  Change in wavelength source to observer can be given as,

$$\Delta\lambda = \lambda_s - \lambda_0$$

$$\Delta\lambda = \lambda_s - \left(\lambda_s - \frac{v_s \lambda_s}{c}\right)$$

$$\boldsymbol{\Delta\lambda} = \left(\boldsymbol{\frac{v_s \lambda_s}{c}}\right)$$

  Here, v_s is source velocity.

Doppler Effect and Velocity measurement by RADAR sensors:

Doppler effect is used to measure speed in RADAR sensors. When the fixed-frequency radio wave sent from the sender continuously strikes an object that is moving towards or away from the sender, the frequency of the reflected radio wave will be changed. This frequency shift is known as Doppler effect, as shown in Fig. 3. The presence and the speed of the moving object can be obtained from the difference in frequency between the transmitted and the reflected radio waves.

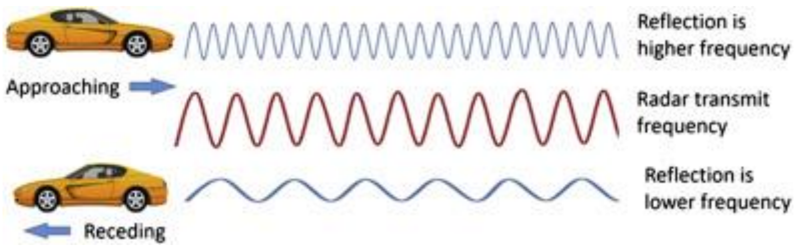


Figure 3- illustration of change in wavelength received to wavelength transmitted

https://www.neltronics.com.au/wp-content/uploads/doppler.png

A basic speed calculation principle by RADAR is just by a radio transmitter and receiver combined into one unit. A radio transmitter is a device that oscillates an electrical current, so the voltage fluctuates at a certain frequency. This electricity generates electromagnetic energy, and when the current is oscillated, the energy travels through the air as an electromagnetic wave. A transmitter also has an amplifier that increases the intensity of the electromagnetic energy and an antenna that broadcasts it into the air.

A radio receiver is just the reverse of the transmitter, it picks up electromagnetic waves with an antenna and converts them back into an electrical current. At its heart, this is all radio is — the transmission of electromagnetic waves through space.

Radar is the use of radio waves to detect and monitor various objects.

The simplest function of radar is to tell you how far away an object is. To do this, the radar device emits a concentrated radio wave and listens for any echo. If there is an object in the path of the radio wave, it will reflect some of the electromagnetic energy, and the radio wave will bounce back to the radar device. Radio waves move through the air at a constant speed, so the radar device can calculate how far away the object is based on how long it takes the radio signal to return.

Radar measures the speed of an object, due to a phenomenon called Doppler shift. Like sound waves, radio waves have a certain frequency, the number of oscillations per unit of time. When the radar gun and the car are both standing still, the echo will have the same wave frequency as the original signal. Each part of the signal is reflected when it reaches the car, mirroring the original signal exactly. But when the car is moving, each part of the radio signal is reflected at a different point in space, which changes the wave pattern. When the car is moving away from the radar gun, the second segment of the signal will travel a greater distance to reach the car than the first segment of the signal.

If the car is moving toward the radar gun, the second segment of the wave travels a shorter distance than the first segment before being reflected. As a result, the peaks and valleys of the wave get squeezed together: The frequency increases. Based on how much the frequency changes, a radar gun can calculate with the help of formula derived above $\Delta\lambda = \left(\frac{v_s \lambda_s}{c}\right)$, how quickly a car is moving toward it or away from it.

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