The 'NeeeeeoowwM' Effect

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Abstract:

This project explores the concept of the Doppler Effect, its principles and mechanisms. It discusses the phenomenon's significance in various contexts, from sound waves produced by moving vehicles to light waves emitted by celestial objects. Additionally, the paper explores the applications of the Doppler Effect in understanding motion and advancing technology across a wide range of disciplines.

Introduction

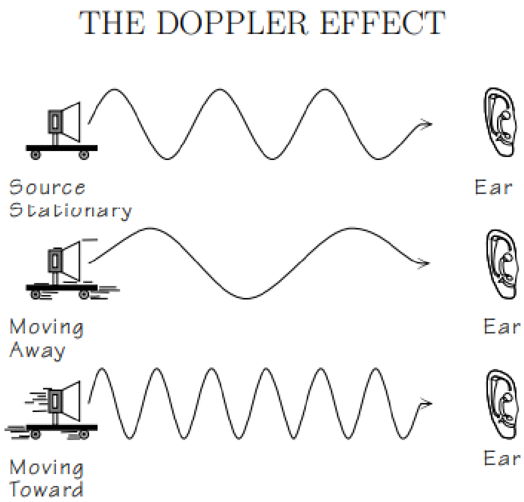
The Doppler effect (or Doppler shift), named after Austrian physicist Christian Doppler who proposed it in 1842 in Prague for light waves, is the change in frequency of a wave in relation to an observer who is moving relative to the source of the wave. The Doppler effect also describes the change in frequency that is observed when there is relative motion between a sound source and an observer

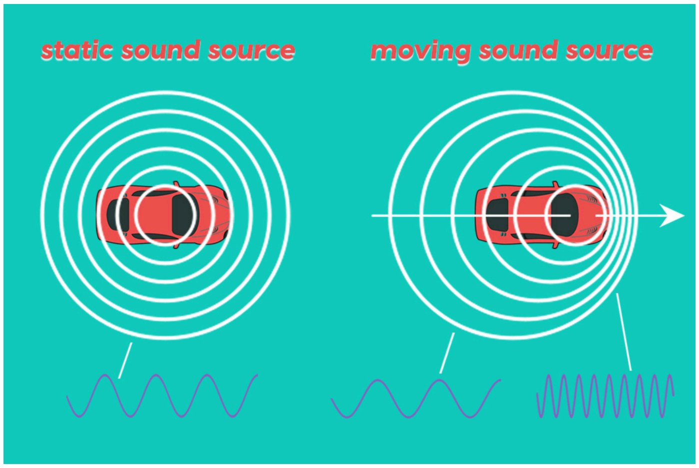
It is commonly heard when a vehicle sounding a siren or horn approaches, passes, and recedes from an observer. The received frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is lower during the recession. The relative changes in frequency can be explained as follows.

When the source of the waves is moving toward the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave. The time between the arrival of successive wave crests at the observer is thus reduced, causing an increase in the frequency.

While they are traveling, the distance between successive wave fronts is reduced; so the waves "bunch together". Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wave fronts is increased, so the waves "spread out". For waves that propagate in a medium, such as sound waves, the velocity of the observer and of the source is relative to the medium in which the waves are transmitted.

The total Doppler Effect may, therefore, result from motion of the source, motion of the observer, or motion of the medium. Each of these effects is analyzed separately. For waves which do not require a medium, such as light or gravity in general relativity, only the relative difference in velocity between the observer and the source needs to be considered. When this relative velocity is not negligible compared to the speed of light, a more complicated relativistic Doppler effect arises.





Development:

Christian Doppler, an austrian mathematician and physicist, first proposed the doppler effect in 1842 in his treatise "Über das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels" on the coloured light of the binary stars and some other stars of the heavens. The hypothesis was tested for sound waves by Dutch meteorologist Christophorus Buys-Ballot in 1845.

Buys-Ballot assembled a group of musicians on a train and stood on the train platform. The musicians were asked to play a single note while the train passed by the platform at full speed and he was able to detect the Doppler effect. He confirmed that the sound's pitch was higher than the emitted frequency when the sound source approached him, and lower than the emitted frequency when the sound source receded from him.

A similar phenomenon was documented independently for electromagnetic waves in an experiment performed by Armand H. L. Fizeau in 1848. In France, the effect is sometimes called "effet Doppler-Fizeau" but that name was not adopted by the rest of the world as Fizeau's discovery was six years after Doppler's proposal. In Britain, John Scott Russell made an experimental study of the Doppler effect in 1848.

Ueber das

farbige Licht der Doppelsterne

und einiger anderer

Gestirne des Himmels.

Versuch einer das Bradley'sche Aberrations-Theorem als integrirenden Theil in sich schliessenden allgemeineren Theorie.

Von

Christian Doppler,

Professor der Mathematik und praktischen Geometrie am technischen Institute und ausserordentl. Mitglied der königl. böhm. Gesellschaft der Wissenschaften.

(Aus den Abhandlungen der k. böhm. Gesellschaft der Wissenschaften (V Folge, Bd. 2) besonders abgedruckt.)

Prag, 1842.

In Commission bei Borrosch & André.

Equation:

The most generalized form of the Doppler effect is given in terms of the resonant frequency and the appropriate velocity components. The observed frequency f is related to the emitted frequency of the source f_0 by the equation:

$$f = f_0 \frac{v \pm v_r}{v \pm v_s},$$

where v is the velocity of waves in the medium, v_s is the velocity of the source relative to the medium and v_r is the velocity of the receiver relative to the medium.

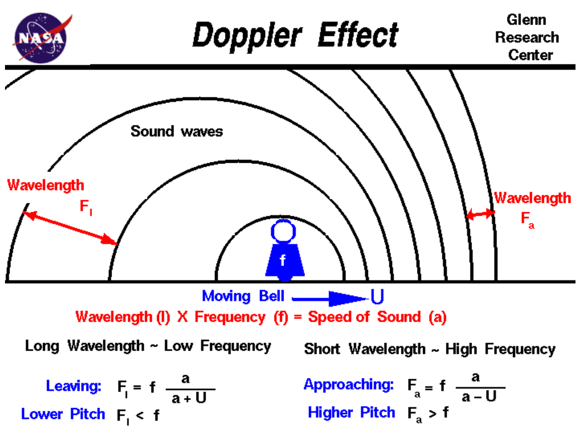
In the case of a stationary receiver (or microphone), the equation reduces to:

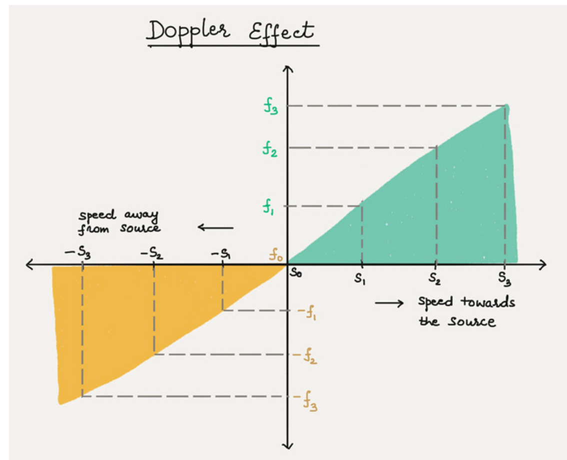
$$f = f_0 \frac{v}{v \pm v_s},$$

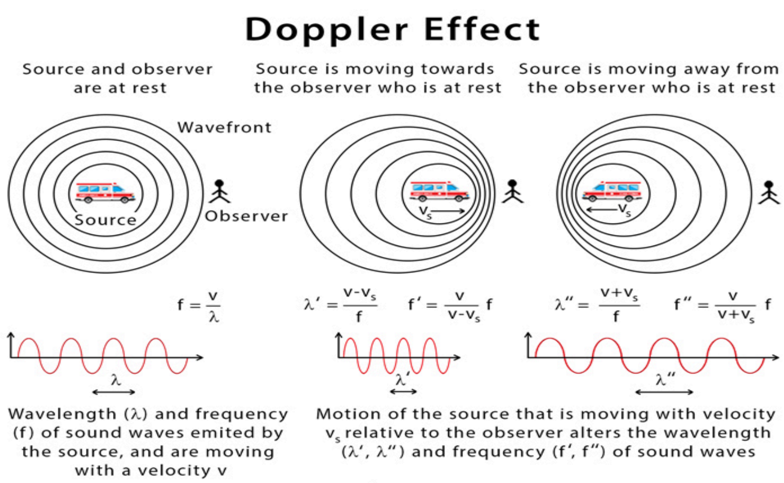
where v_s is positive when the source is moving away from the observer, and negative when moving towards the observer. These equations assume that the source is directly approaching or receding from the observer.

A similar analysis for a moving observer and a stationary source (in this case, the wavelength keeps constant, but due to the motion, the rate at which the observer receives waves and hence the transmission velocity of the wave [with respect to the observer] is changed) yields the observed frequency:

$$f = f_0 \frac{v \pm v_r}{v}$$







Types of Doppler Effect

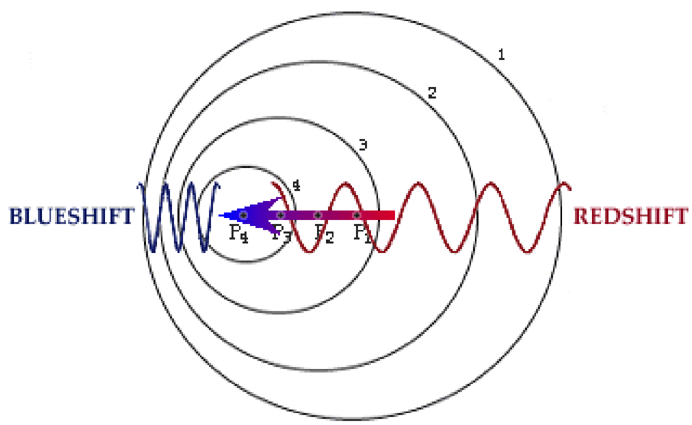
Classical Doppler Effect:

The classical doppler effect is the shift in frequency (and wavelength) perceived by a receiver in relative motion to a wave source. One can find different ways to derive a formula relating the received frequency to the emitted frequency. This applies to sound waves.

Doppler Effect in Light:

Unlike sound waves, light waves do not require a medium for travel, so the classical application of the Doppler effect doesn't apply precisely to this situation. Therefore, the key difference between doppler effect in sound and light is that for the doppler effect in sound, the velocity of the observer and the source are relative to the medium in which the waves go through whereas for the doppler effect in light, only the relative difference in velocity between the observer and the source are important. This is why we analyze the Doppler effect for light in terms of the motion of the source relative to the listener.

Additionally, the Doppler effect for light waves is usually described in terms of colors rather than frequency. A red shift occurs when the source and observer are moving away from each other, and a blue shift occurs when the source and observer are moving towards each other. Edwin Hubble used the Doppler Effect to determine that the universe expands. Hubble found out the light between the galaxies shifted toward higher frequencies or the red end of the spectrum. This is known as a red Doppler shift, or the red-shift. If the galaxies were moving toward him then the light observed would be blue-shifted.



The Relativistic Doppler Effect:

The Relativistic Doppler Effect is the change in frequency (and wavelength) of light, caused by the relative motion of the source and the observer (as in the classical Doppler Effect), when taking into account effects described by the special theory of relativity. The relativistic Doppler Effect is different from the non-relativistic Doppler Effect as the equations include the time dilation effect of special relativity and do not involve the medium of propagation as a reference point. They describe the total difference in observed frequencies and possess the required Lorentz symmetry.

Doppler effect for light

$$\nu_{observed} = \left[\frac{\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v}{c}}\right]\nu_{source}$$

which can be rearranged to the form

$$\nu_{observed} = \nu_{source}\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$$

or in common relativity notation:

$$\nu_{observed} = \nu_{source}\sqrt{\frac{1+\beta}{1-\beta}}$$

Doppler effect for sound

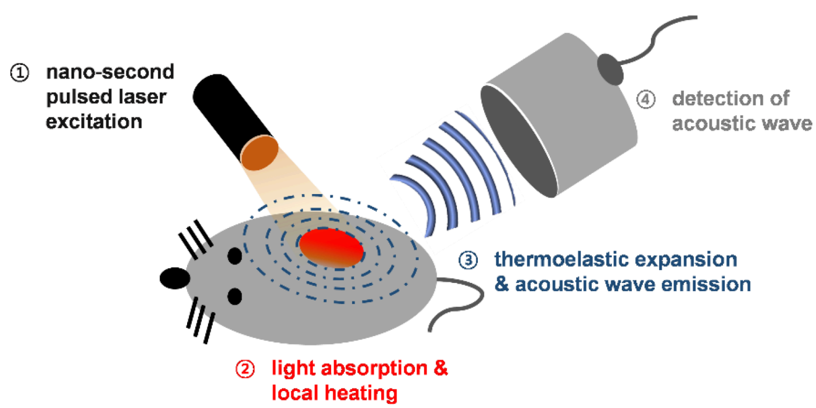
$$f_{observed} = \left[\frac{v}{v \pm v_{source}}\right] f_{source}$$

which when changed to the normal notation for light waves becomes

$$\nu_{observed} = \nu_{source}\left[\frac{1}{1 \pm \frac{v_{source}}{v_{wave}}}\right]$$

The Photoacoustic Doppler Effect:

The photoacoustic Doppler Effect, as its name implies, is one specific kind of Doppler Effect, which occurs when an intensity modulated light wave induces a photoacoustic wave on moving particles with a specific frequency. The observed frequency shift is a good indicator of the velocity of the illuminated moving particles. A potential biomedical application is measuring blood flow.



Specifically, when an intensity modulated light wave is exerted on a localized medium, the resulting heat can induce an alternating and localized pressure change. This periodic pressure change generates an acoustic wave with a specific frequency. Among various factors that determine this frequency, the velocity of the heated area and thus the moving particles in this area can induce a frequency shift proportional to the relative motion. Thus, from the perspective of an observer, the observed frequency shift can be used to derive the velocity of illuminated moving particles.

Applications of the Doppler Effect

Sirens:

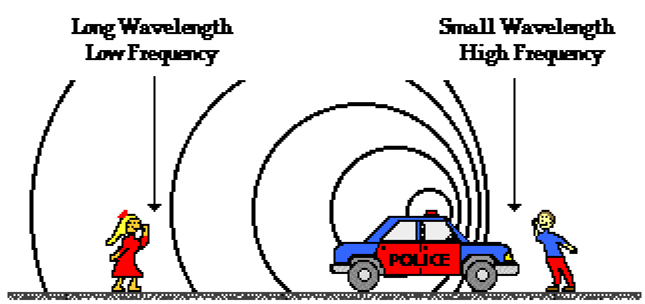
The siren on a passing emergency vehicle will start out higher than its stationary pitch, slide down as it passes, and continue lower than its stationary pitch as it recedes from the observer.

Astronomer John Dobson explained the effect thus: "The reason the siren slides is because it doesn't hit you." In other words, if the siren approached the observer directly, the pitch would remain constant (as $v_{s,r}$ is only the radial component) until the vehicle hit him, and then immediately jump to a new lower pitch.

Because the vehicle passes by the observer, the radial velocity does not remain constant, but instead varies as a function of the angle between his line of sight and the siren's velocity:

$$v_r = v_s \cdot \cos\theta$$

where v_s is the velocity of the object (source of waves) with respect to the medium, and θ is the angle between the object's forward velocity and the line of sight from the object to the observer.



Robotics:

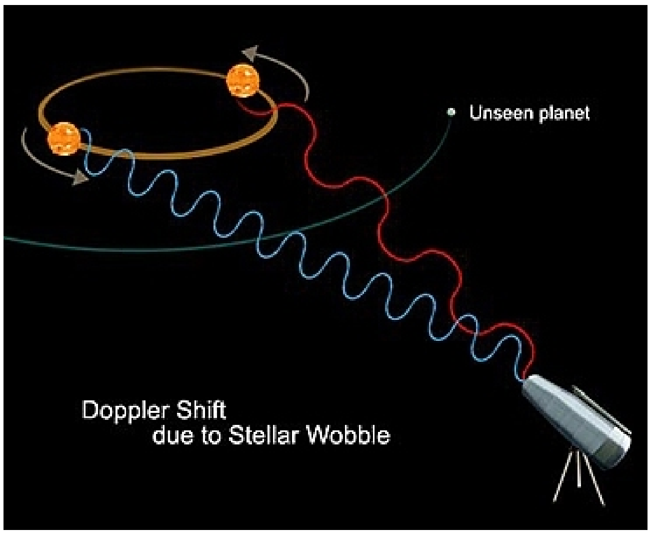
Dynamic real-time path planning in robotics to aid the movement of robots in a sophisticated environment with moving obstacles often takes help of the Doppler effect. Such applications are specially used for competitive robotics where the environment is constantly changing, such as robot soccer.

Astronomy:

Redshift of spectral lines in the optical spectrum of a supercluster of distant galaxies (right), as compared to that of the Sun (left). The Doppler Effect for electromagnetic waves such as light is of great use in astronomy and results in either a so-called red shift or blue shift. It has been used to measure the speed at which stars and galaxies are approaching or receding from us, that is, the radial velocity.

This is used to detect if an apparently single star is, in reality, a close binary and even to measure the rotational speed of stars and galaxies. The use of the Doppler Effect for light in astronomy depends on our knowledge that the spectra of stars are not continuous. They exhibit absorption lines at well defined frequencies that are correlated with the energies required to excite electrons in various elements from one level to another. The Doppler Effect is recognizable in the fact that the absorption lines are not always at the frequencies that are obtained from the spectrum of a stationary light source. Since blue light has a higher frequency than red light, the spectral lines of an approaching astronomical light source exhibit a blue shift and those of a receding astronomical light source exhibit a redshift.

Among the nearby stars, the largest radial velocities with respect to the Sun are +308 km/s (BD-15°4041, also known as LHS 52, 81.7 light-years away) and -260 km/s (Woolley 9722, also known as Wolf 1106 and LHS 64, 78.2 light-years away). Positive radial velocity means the star is receding from the Sun, negative that it is approaching.



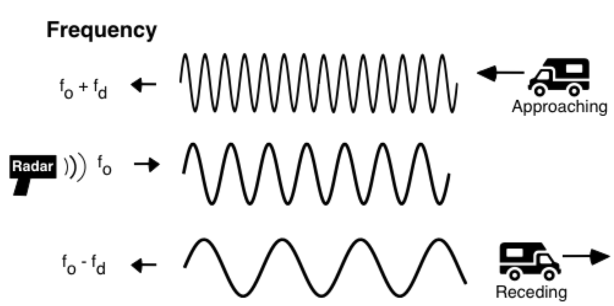
Temperature measurement:

Another use of the Doppler Effect, which is found mostly in plasma physics and astronomy, is the estimation of the temperature of a gas (or ion temperature in a plasma) which is emitting a spectral line. Due to the thermal motion of the emitters, the light emitted by each particle can be slightly red or blue-shifted, and the net effect is a broadening of the line. This line shape is called a Doppler profile and the width of the line is proportional to the square root of the temperature of the emitting species, allowing a spectral line (with the width dominated by the Doppler broadening) to be used to infer the temperature.

Radar:

The Doppler Effect is used in some types of radar, to measure the velocity of detected objects. A radar beam is fired at a moving target — e.g. a motor car, as police use radar to detect speeding motorists — as it approaches or recedes from the radar source. Each successive radar wave has to travel farther to reach the car, before being reflected and re-detected near the source. As each wave has to move farther, the gap between each wave increases, increasing the wavelength.

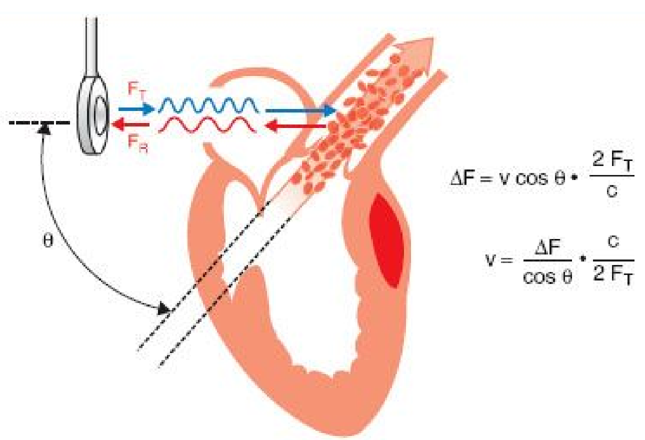
In some situations, the radar beam is fired at the moving car as it approaches, in which case each successive wave travels a lesser distance, decreasing the wavelength. In either situation, calculations from the Doppler Effect accurately determine the car's velocity. Moreover, the proximity fuze, developed during World War II, relies upon Doppler radar to explode at the correct time, height, distance, etc.

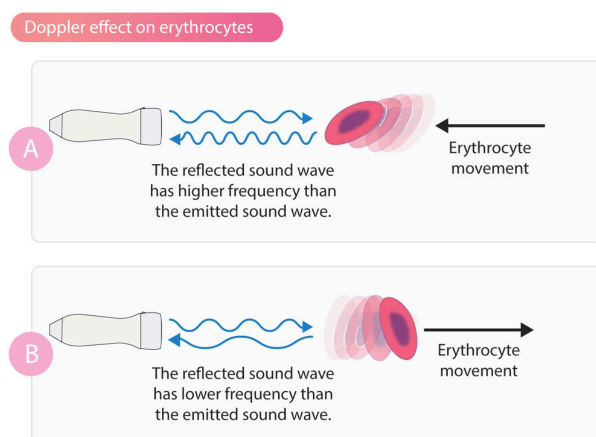


Medical Imaging and Blood Flow Velocity Measurement:

Color flow ultrasonography (Doppler) of a carotid artery - scanner and screen. An echocardiogram can, within certain limits, produce accurate assessment of the direction of blood flow and the velocity of blood and cardiac tissue at any arbitrary point using the Doppler Effect. One of the limitations is that the ultrasound beam should be as parallel to the blood flow as possible. Velocity measurements allow assessment of cardiac valve areas and function, any abnormal communications between the left and right side of the heart, any leaking of blood through the valves (valvular regurgitation), and calculation of the cardiac output. Contrast-enhanced ultrasound using gas-filled microbubble contrast media can be used to improve velocity or other flow-related medical measurements.

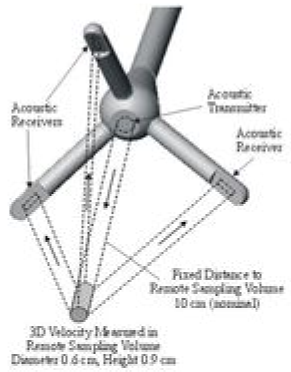
Although "Doppler" has become synonymous with "velocity measurement" in medical imaging, in many cases it is not the frequency shift (Doppler shift) of the received signal that is measured, but the phase shift (when the received signal arrives). Velocity measurements of blood flow are also used in other fields of medical ultrasonography, such as obstetric ultrasonography and neurology. Velocity measurement of blood flow in arteries and veins based on Doppler Effect is an effective tool for diagnosis of vascular problems like stenosis.





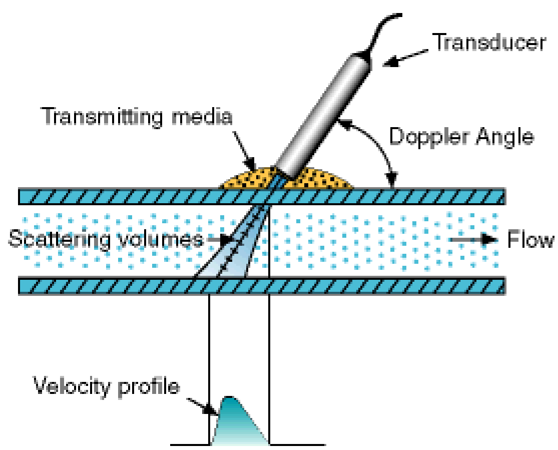
Flow Measurement:

Instruments such as the laser Doppler Velocimeter (LDV), and Acoustic Doppler Velocimeter (ADV) have been developed to measure velocities in a fluid flow. The LDV emits a light beam and the ADV emits an ultrasonic acoustic burst, and measures the Doppler shift in wavelengths of reflections from particles moving with the flow. The actual flow is computed as a function of the water velocity and phase. This technique allows non-intrusive flow measurements, at high precision and high frequency.



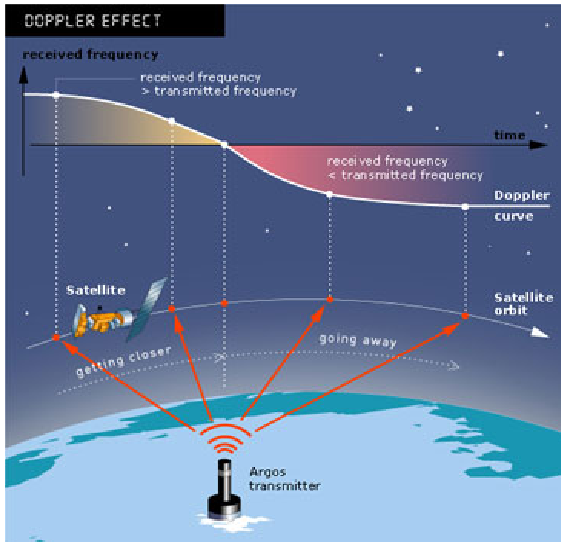
Velocity Profile Measurement:

Developed originally for velocity measurements in medical applications (blood flow), Ultrasonic Doppler Velocimetry (UDV) can measure in real time the complete velocity profile in almost any liquids containing particles in suspension such as dust, gas bubbles, emulsions. Flows can be pulsating, oscillating, laminar or turbulent, stationary or transient. This technique is fully non-invasive.



Satellite communication:

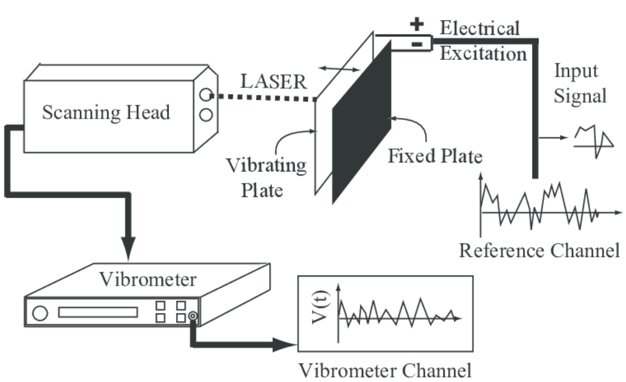
Fast moving satellites can have a Doppler shift of dozens of kilohertz relative to a ground station. The speed, thus magnitude of Doppler Effect, changes due to earth curvature. Dynamic Doppler compensation, where the frequency of a signal is changed multiple times during transmission, is used so the satellite receives a constant frequency signal.



Vibration measurement:

A Laser Doppler Vibrometer (LDV) is a non-contact method for measuring vibration. The laser beam from the LDV is directed at the surface of interest, and the vibration amplitude and frequency are extracted from the Doppler shift of the laser beam frequency due to the motion of the surface. A laser Doppler vibrometer (LDV) is a scientific instrument that is used to make non-contact vibration measurements of a surface.

The laser beam from the LDV is directed at the surface of interest, and the vibration amplitude and frequency are extracted from the Doppler shift of the laser beam frequency due to the motion of the surface. The output of an LDV is generally a continuous analog voltage that is directly proportional to the target velocity component along the direction of the laser beam. Some advantages of an LDV over similar measurement devices such as an accelerometer are that the LDV can be directed at targets that are difficult to access, or that may be too small or too hot to attach a physical transducer. Also, the LDV makes the vibration measurement without mass-loading the target, which is especially important for MEMS devices.

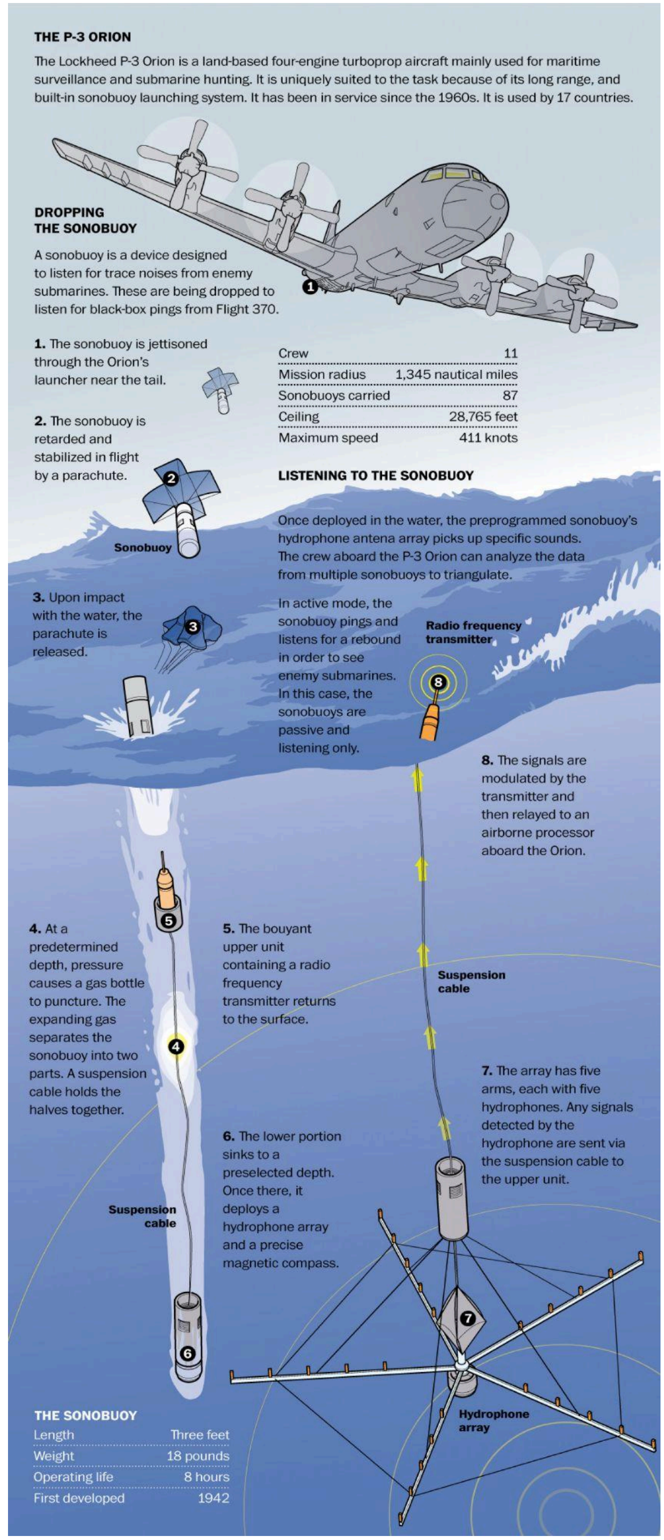


Underwater acoustics:

In military applications, the Doppler shift of a target is used to ascertain the speed of a submarine using both passive and active sonar systems. As a submarine passes by a passive sonobuoy, the stable frequencies undergo a Doppler shift, and the speed and range from the sonobuoy can be calculated. If the sonar system is mounted on a moving ship or another submarine, then the relative velocity can be calculated.

A sonobuoy (a portmanteau of sonar and buoy) is a relatively small (typically 5 inches / 13 centimeters, in diameter and 3 ft/91 cm long) expendable sonar system that is dropped/ejected from aircraft or ships conducting anti-submarine warfare or underwater acoustic research. The buoys are ejected from aircraft in canisters and deploy upon water impact.

An inflatable surface float with a radio transmitter remains on the surface for communication with the aircraft, while one or more hydrophone sensors and stabilizing equipment descend below the surface to a selected depth that is variable, depending on environmental conditions and the search pattern. The buoy relays acoustic information from its hydrophone(s) via UHF/VHF radio to operators onboard the aircraft.



Limitations of Doppler Effect

Limitations of Doppler effect in sound are as follows:

1. The velocity of source of sound must be less than that of the velocity of sound i.e. v_s less than v.
2. The velocity of the observer must be less than the velocity of sound i.e. $v_o < v$.
3. If the velocity of sound of source is greater than that of velocity of sound then due to shock waves, the wave front gets distorted. Consequently, the change in frequency will not be observed by the observer.

Conclusion

The Doppler effect has a great impact on our lives. It has helped us explain several phenomena that are happening before us. Its numerous applications in different areas of modern science from flow measurement, and vibration measurement, to satellite communications, and monitoring hurricane strengths to developmental biology and identification of cancer make it one of the most common scientific concepts that we witness and use in our daily lives. Thus, we can safely say that the Doppler effect is one of the greatest discoveries of science.

Bibliography

Petrescu. (2012). *A New Doppler Effect*. Germany: Books on Demand GmbH. https://doi.org/10.13140/RG.2.1.1142.8560

Paik. (2021). *Doppler Effect and its Application*. India. https://doi.org/10.13140/RG.2.2.13553.61282

Lowry, R., & Teske, C. (2009). An Experimental Study of a Table-Top Doppler Effect Simulation. : Worcester Polytechnic Institute.

CM Physics Project: Doppler Effect. (n.d.). Retrieved from https://www.ionaphysics.org/lab/Doppler/

Larsen. (2002, April 17). The Doppler Effect. Retrieved from https://www.physnet.org/modules/pdf_modules/m204.pdf

Doppler Effect. (n.d.). Retrieved from https://galileo.phys.virginia.edu/classes/152.mf1i.spring02/DopplerEffect.htm

The Doppler Effect. (n.d.). Retrieved from https://www.phys.uconn.edu/~gibson/Notes/Section6_3/Sec6_3.htm