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Research on the Doppler Effect from Classical to Relativistic and Its Applications

Jinyu Wan

Chengdu Shude High School Foreign Language Campus, Chengdu, China
3951764459@qq.com

Abstract. The Doppler effect describes the phenomenon where the relative motion between a wave source and an observer causes a change in the received frequency, and it has important applications in fields like sound wave propagation, astronomical observation, and precision measurement. However, the classical Doppler theory is established on the classical spacetime framework and the assumption of wave propagation through a medium, limiting its ability to explain the frequency changes of waves under high-speed motion conditions. This paper explores the connections and differences between the classical Doppler effect and the relativistic Doppler effect, and analyzes the corrections made by special relativity to the shift laws of light waves and their practical applications. By reviewing relevant physical literature, this study analyzes relativistic frequency shifts based on classical Doppler theory, Lorentz transformations, and the relativistic Doppler effect, with applications in cosmological redshift, stellar spectra, CMB radiation, satellite navigation, and high-speed motion measurements. The results show that classical Doppler theory remains applicable to low-speed mechanical waves, while the relativistic Doppler effect explains light frequency shifts in high-speed and transverse motion through time dilation and Lorentz transformations. In practice, it enables applications such as celestial velocity measurement, satellite time correction, and high-precision optical clock correction, while further refinement is required for strong gravitational fields and higher-precision measurements.

Keywords: Doppler effect, Special relativity, Lorentz transformation, Relativistic Doppler shift, Spectral observation

1. Introduction

The Doppler effect was first proposed by Christian Doppler in 1842 to describe the phenomenon where the frequency of waves received by an observer changes when there is motion between the wave source and the observer [1]. The classical Doppler effect is built on the classical view of space and time and the assumption of a propagation medium, making it applicable mainly to mechanical waves such as sound. The observed frequency shift depends on the relative motion between the source, observer, and medium. However, as light propagates in vacuum without a fixed medium, the classical reference frame cannot describe its propagation. Moreover, the classical velocity addition law fails at velocities approaching the speed of light, and classical theory cannot explain frequency shifts caused by transverse motion. Special relativity addresses these limitations via Lorentz

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transformations and time dilation, establishing the relativistic Doppler effect for light waves [2]. It describes longitudinal and transverse frequency shifts. Under low-speed conditions, the relativistic Doppler formula reduces to the classical form, showing consistency between the two theories. Therefore, this study examines the limits of classical Doppler theory for light propagation and relativistic corrections from special relativity. In addition, relevant cases, including cosmic redshift, stellar spectral observations, cosmic microwave background radiation, and satellite navigation systems, are discussed to evaluate the role of the relativistic Doppler effect in high-speed motion and precision measurement.

2. Fundamentals of classical and relativistic Doppler effects

2.1. Models and limitations of classical Doppler effect theory

The classical Doppler effect describes the change in received frequency caused by the relative motion between the wave source and the observer [1]. For mechanical waves such as sound waves, it is based on the assumption of a propagation medium, where the observed frequency depends on the motion of both the source and observer relative to the medium [3]. In the one-dimensional case, its frequency relationship can be expressed as:

$$f' = f \times \frac{V - V_o}{V - V_s} \tag{1}$$

where f' is the frequency received by the observer, f is the intrinsic frequency emitted by the wave source, V is the propagation speed of the wave in the medium V_o is the velocity of the observer relative to the medium, and V_s is the velocity of the wave source relative to the medium. For sound wave propagation in a stationary medium, this formula can well describe the frequency change caused by the relative motion between the source and the observer

However, when this theory is applied to light waves, its applicability is limited. Light waves can propagate in a vacuum without depending on a medium like sound waves so the medium reference frame in classical theory cannot be used to describe the propagation of light [3]. In addition, at high speeds approaching the speed of light, the classical velocity addition law no longer applies, leading to discrepancies between theoretical predictions and experimental results. It also fails to explain the frequency change phenomenon occurring under conditions of transverse relative motion, motivating the development of the relativistic Doppler theory.

2.2. Reformulation of spacetime structure in special relativity

In classical mechanics, time and space are seen as absolute quantities, and transformations between reference frames are described by Galilean transformations. However, this framework cannot explain light propagation at high speeds, as experiments show that the speed of light in vacuum is independent of the observer's motion [4]. Therefore, special relativity introduced the principles of light-speed invariance and relativity, replacing Galilean transformations with Lorentz transformations [2].

Among them, the principle of the constancy of the speed of light states that the speed of light in a vacuum remains constant in all inertial reference frames; the principle of relativity states that the laws of physics have the same form in all inertial reference frames. Based on these two postulates, the Lorentz transformation replaces the Galilean transformation, and its expression is:

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$$x'=\gamma(x-vt) \tag{2}$$

$$t'=\gamma(t-\frac{v}{c^2}x) \tag{3}$$

where $\gamma=\frac{1}{\sqrt{1-\beta^2}}$ is the Lorentz factor, and $\beta=\frac{v}{c}$ is the ratio of the relative velocity to the speed of light. The Lorentz transformation predicts that measurements of time and space depend on the observer's motion. The time dilation effect is expressed as:

$$\Delta t=\gamma\,\Delta\,t_0 \tag{4}$$

This effect indicates that the time interval in the moving reference frame is dilated when observed from other inertial reference frames. Since the frequency of light is the reciprocal of its oscillation period, time dilation leads to differences in the measured light frequency across different reference frames. Thus, even transverse motion between the light source and observer can produce a frequency shift, known as the transverse Doppler effect [2, 5].

2.3. Unified formulation of the relativistic Doppler effect

Based on the Lorentz transformation and the constancy of the speed of light, the relativistic Doppler effect describes the frequency shift between a light source and an observer in relative motion [2]. The intrinsic frequency emitted by the light source is denoted as f_0, the relative velocity between the light source and the observer is denoted as v, and $\beta=v/c$ is defined, where c represents the speed of light. If the angle between the velocity direction and the light propagation direction is θ, then the frequency received by the observer is:

$$f=f_0\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \tag{5}$$

where β represents the ratio of the relative velocity to the speed of light. When the motion velocity is much smaller than the speed of light ($\beta\ll 1$), the formula can be approximately simplified to the classical Doppler formula, indicating that the relativistic theory is consistent with the classical theory under low-speed conditions [5]. For motion along the line of sight ($\theta=0°$ or $180°$), the relativistic Doppler effect appears as a longitudinal frequency shift. The received frequency increases when the light source approaches the observer and decreases when it moves away, expressed as:

$$f=f_0\sqrt{\frac{1+\beta}{1-\beta}}\,(\text{blue shift}),\ f=f_0\sqrt{\frac{1-\beta}{1+\beta}}\,(\text{red shift}) \tag{6}$$

When the light source and the observer are in transverse relative motion, i.e., $\theta=90°$, a frequency shift still occurs due to time dilation, even without a line-of-sight velocity component.

$$f=f_0\sqrt{1-\beta^2} \tag{7}$$

This transverse Doppler effect results from time dilation and cannot be explained by classical Doppler theory. It has been verified in high-speed atomic spectroscopy experiments and precision

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optical measurements [5].

3. Relativistic redshift properties at cosmological scales

3.1. Redshift observations from cosmic expansion

Hubble's observations showed that spectral lines of most extragalactic galaxies shift toward longer wavelengths, with larger redshifts observed for more distant galaxies [6]. This phenomenon is mainly linked to cosmic expansion, which stretches the wavelength of light during propagation. In addition, the local motion of galaxies relative to surrounding matter also contributes to the observed Doppler shift. For relatively nearby galaxies, where the recession velocity is much smaller than the speed of light, the redshift can be approximated as:

$$z \approx \frac{v}{c} \tag{8}$$

where z is the redshift, v is the velocity of the galaxy relative to the observer, and c is the speed of light. Under this condition, the Doppler effect can describe the relationship between redshift and the velocity of celestial bodies [7]. However, for distant high-redshift galaxies, cosmic expansion plays a dominant role, requiring relativistic models to describe frequency changes during light propagation.

Spectral line measurements therefore provide a method for determining the radial velocities and motion characteristics of celestial objects.

3.2. Redshift and blueshift signatures in celestial spectra

In the study of stars and compact objects, the frequency shift of spectral lines can be used to measure the motion velocity of celestial bodies along the line of sight. When a star approaches or recedes from an observer, its characteristic spectral lines will undergo a blueshift or redshift, respectively. By measuring the change in the position of spectral lines, the radial velocity of the star can be calculated; this method is widely used in the orbital analysis of binary star systems and the detection of exoplanets [8]. In high-precision spectroscopic observations, the measurement precision of spectral line shifts can reach the meter-per-second level, enabling researchers to detect minute motions on stellar surfaces caused by planets.

For high-speed systems such as neutron stars and black hole accretion disks, the material moves at a significant fraction of the speed of light, at which point the relativistic Doppler effect significantly affects the observed spectral shape [9]. Due to the different directions and velocities of motion in different regions of the accretion disk, the matter on the side facing the observer produces a blueshift, while the matter on the side moving away from the observer produces a redshift, thereby leading to line broadening and asymmetric changes [9]. By analyzing these spectral features, the rotation speed of the accretion disk can be estimated, and the motion of matter near the black hole can be studied in conjunction with other observations.

3.3. Frequency shifts in the cosmic microwave background radiation

As a remnant of the early universe, the Cosmic Microwave Background (CMB) is electromagnetic radiation observed today with an average temperature of approximately 2.7 K. According to the theory of blackbody radiation, the radiation temperature is related to the photon frequency distribution, meaning that frequency shifts are reflected as temperature variations in observations.

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Based on this relationship, all-sky observations have demonstrated a dipole anisotropy in the CMB temperature distribution, with the temperature being slightly higher in one direction and lower in the opposite direction [10].

This phenomenon is primarily caused by the motion of the Earth relative to the CMB rest frame. When the direction of observation is the same as the direction of the Earth's motion, photons are shaped by the relativistic Doppler effect, the observed frequency increases, and the CMB temperature appears to rise; when the direction of observation is opposite to the direction of motion, the photon frequency decreases, and the temperature appears to drop. Therefore, the direction and amplitude of the CMB dipole signal can reflect the motion of the observer relative to the CMB frame. In the low-velocity approximation, the temperature change and velocity satisfy:

$$\frac{\Delta T}{T} \approx \frac{v}{c} \tag{9}$$

where ΔT is the temperature change, T is the average CMB temperature, and v is the velocity of the Earth relative to the CMB rest frame. Thus, the velocity of the Earth's motion can be calculated by analyzing the dipole term of the all-sky temperature distribution. And observations from the Planck satellite show that this velocity is approximately 369 km/s, which is consistent with the theoretical prediction of the relativistic Doppler effect [11].

4. Relativistic effects in precision timing and high-velocity motion

4.1. Relativistic time corrections in satellite navigation systems

The positioning process of Global Navigation Satellite Systems (such as GPS and BeiDou) relies on precise time synchronization between satellites and receivers. As navigation satellites orbit the Earth at a speed of approximately 3.8 km/s, their onboard atomic clocks are affected by relativistic effects [12]. The satellite motion causes special relativistic time dilation, making the clocks run about 7.2 μs slower per day. Meanwhile, the weaker gravitational field at high orbital altitudes produces a general relativistic redshift, causing the clocks to run about 45.9 μs faster per day [13]. The combined effect makes satellite clocks run about 38.7 μs faster per day than ground clocks. Without correction, this difference would accumulate and cause positioning errors of about 11 km per day. Thus, relativistic corrections are applied to satellite clock frequencies to maintain synchronization with ground time standards.

4.2. Relativistic frequency shift corrections in high-velocity motion measurement

Under high-speed motion conditions, the emitted or received light frequency changes due to the relativistic Doppler effect, requiring corrections based on relativistic formulas [3]. The Ives-Stilwell experiment in 1938 observed the frequency change in the transverse motion case by measuring the frequency shift of high-speed moving hydrogen atoms [5]. The experimental results were consistent with the predictions of special relativity, verifying the transverse Doppler effect caused by time dilation. Subsequently the Mössbauer effect improved the precision of gamma-ray frequency shift measurements, enabling researchers to test the relativistic frequency shift law with higher accuracy. In rotating disk experiments, by utilizing the motion between high-speed moving sources and receiving devices, the relationship between frequency shift and velocity can be measured and compared with theoretical calculations. In particle accelerators, the motion speed of charged particles is close to the speed of light, and the radiation frequency they produce is affected by the

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relativistic Doppler effect. Therefore, the observed frequency must be corrected according to the particle velocity and combined with relativistic formulas to determine the particle energy and momentum.

4.3. Frequency shift correction in quantum communication and optical clocks

In space-to-ground quantum communication and optical clock experiments, relative motion causes optical frequency shifts. In satellite-to-ground links, the relative velocity between the satellite and ground station introduces Doppler shifts in the received signal [12]. In quantum communication, this frequency shift affects the phase relationship of optical signals. When interferometric measurements or quantum distribution rely on precise phase matching, Doppler compensation is required to reduce its impact on measurement accuracy [14]. In optical clock comparison experiments, where atomic transition frequencies can reach a stability level of 10^{-18}, even small relative motions may introduce measurable frequency shifts. Therefore, frequency corrections based on the relative velocity between satellites or optical clocks are required to ensure accurate comparisons between clocks at different locations.

5. Existing challenges and future development

The relativistic Doppler effect is derived from special relativity in inertial reference frames; however, in strong gravitational fields or complex motion conditions, both motion-induced frequency shifts and gravitational effects must be considered. For example, near neutron stars or black holes, spectral features are influenced by both matter velocity and gravitational redshift, requiring analysis based on general relativity [13]. Although verified in high-speed atomic spectroscopy, particle experiments, and precision optical measurements, the relativistic Doppler effect still faces challenges in extreme velocities and strong gravitational fields due to experimental limitations. In systems like black hole accretion disks, the different velocities and motion directions of matter produce complex blueshift, redshift, and spectral broadening effects, which require theoretical modeling for interpretation [9]. Future advances in high-precision optical clocks, ion storage rings, and space optical measurement technologies will enable more accurate tests of relativistic frequency shifts. Meanwhile, applications in satellite communication, space-to-ground optical links, and precision time synchronization require accurate frequency correction based on relative motion and signal propagation conditions.

6. Conclusion

This paper compares the classical and relativistic Doppler effects in theory and applications. The results show that classical Doppler theory describes mechanical wave frequency shifts at low speeds but is limited by classical space-time and medium assumptions in high-speed and transverse motion. To overcome these limitations, special relativity modifies the frequency shift relationship through Lorentz transformations and time dilation, hence allowing the relativistic Doppler effect to describe frequency shifts under different motion conditions. In practical applications, it supports astronomical velocity measurements, CMB analysis, satellite time correction, and optical frequency compensation. Although the theory has been well verified in weak gravitational fields and high-speed motion experiments, further studies are required for strong gravitational environments and high-precision quantum measurements by incorporating general relativity and more accurate experimental methods. With advances in optical clocks, space-based measurements, and high-energy

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physics experiments, the applications of the relativistic Doppler effect in complex environments will continue to expand.

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