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A demonstration device to simulate the radial velocity method for exoplanet detection

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Abstract

A device for simulating exoplanet detection by the radial method based on the Doppler principle has been constructed. The spectral shift of light from a distant star, mutually revolving with the exoplanet, is simulated by the spectral shift of the sound wave emitted by the device's star approaching and receding relative to the static frequency detector. The detected sound frequency shift reflects the relative velocity of the 'star' very well. Both teachers and students benefit from the radial velocity method and the transit method (published by us previously) provided by this device.

Introduction

The search for planets outside our solar system (exoplanets) is still going on vigorously, especially, ones that have the potential of sustaining life [1]. Two common ways of detecting these planets are the radial velocity method and the transit method. The former is based on the light frequency shift of the star in close association with the planet(s) and the latter is based on partial blocking of light from the star by the transiting planet(s). Recently, there have been pedagogical articles on detecting the exoplanets by the transit method [2–6]

Previously [6] we built apparatus simulating exoplanet detection by the transit method. The device has been successful in helping students to have a tangible glimpse of a detection device, albeit simplified, and a way of obtaining data about the planet. Because of the physical reality of the apparatus [7], one important question was raised by students about certain angles of inclination of the planet which may lead to difficulty or even impossibility of detection by the transit method.

In this article we present a new version of the apparatus, which, while maintaining the possibility of illustrating detection by the transit method, provides a way to simulate the radial velocity detection based on the Doppler effect. Here we use sound wave detection in place of light wave detection and show that the device is also effective in helping students obtain experimental data to learn more about the 'planet'.

The demonstration set-up

The constructed set-up is shown in figure 1. As mentioned earlier this device can simulate both the radial velocity and the transit method. Thus

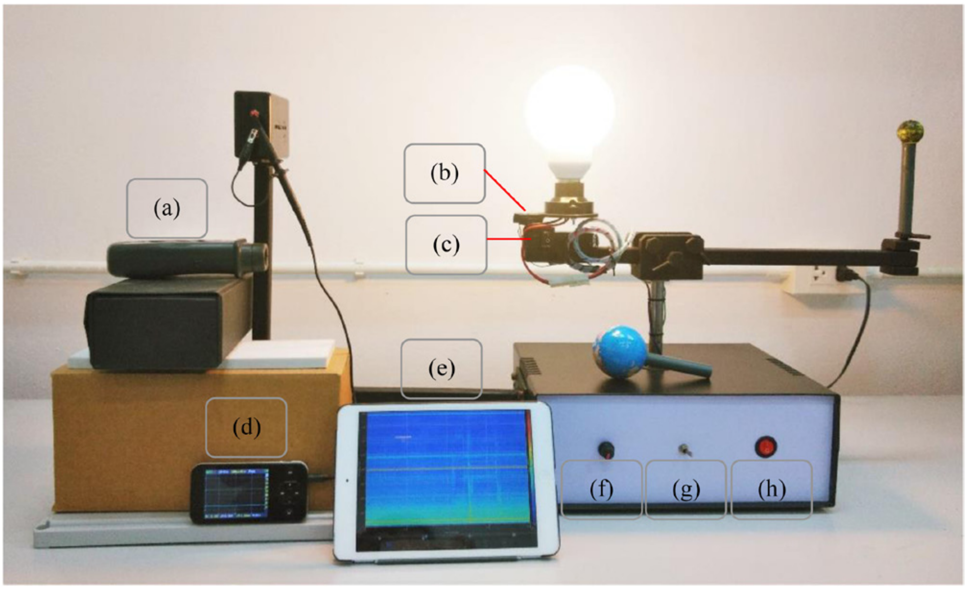


Figure 1. (a) Tachometer, (b) piezo buzzer, (c) on/off switch for buzzer, (d) mini oscilloscope for displaying the square wave signal, (e) spectrumview app on iPad mini, (f) RPM controller, (g) rotation controller and (h) on/off switch for motor.

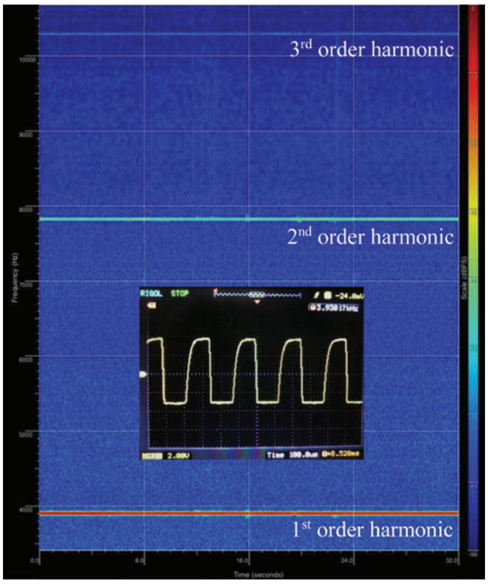
while keeping the light detection components (for the transit method as in [6]) in their former places, here we label only the additional sound detection components relevant to the present radial velocity method.

A light bulb (8 cm) acts as the star and opaque balls (diameters of 4 cm and 2.75 cm) representing two exoplanets of different densities. A piezo buzzer with built-in drive circuit (4.4 ± 0.5 kHz) is attached to the light bulb. The vertical shaft is rotated by a motor causing the rotation of both objects around the center of mass. Periodically the buzzer, the sound frequency of which represents that of light from the star, would approach and recede relative to the detector. The movement is displayed on the *SpectrumView* app on an iPad mini, which is placed 30 cm away from the shaft. The Fourier transformed square wave is shown in figure 2(a). With the help of the *SpectrumView* app of Oxford Wave Research, we can select and focus on each single harmonic desired by zooming in.

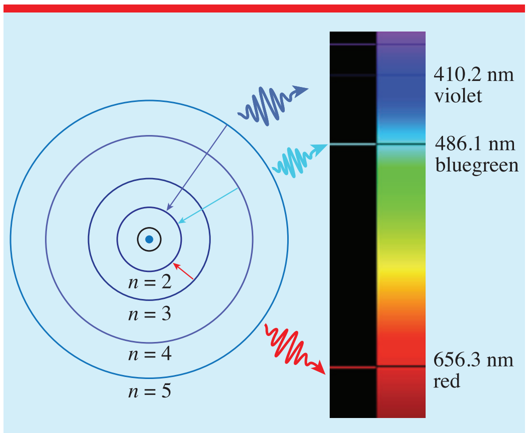
Results and discussion

Both figures 2(a) and (b) show patterns of discrete lines of the respective frequency spectra (of sound and light respectively) but the distances between the lines are different. Light from a star is due to fusion reaction between hydrogen atoms which are excited. The emission spectrum of hydrogen atoms of the star and the characteristic spectral lines consist of the Balmer series (in the visible range), the Lyman series (in the ultraviolet band), the Paschen series (in the infrared band) and the other series. For detecting exoplanets, frequency shifts of the Balmer lines are often used to determine the radial velocity [8]. To simulate the Doppler effect of the star wobble by using sound instead of light from the star, we drive the buzzer to generate square waves to the specified frequency. The square wave pattern is formed from multiple sinusoidal waves (at different frequencies) that exhibit discrete harmonics. All the harmonics of the square wave are shifted by the same fraction rendering the Doppler effect.

The software on iPad minis can display a real-time frequency shift shown in figure 3(a), where the horizontal scale of the Doppler spectrum represents time in seconds. The vertical scale represents the frequency shift in Hz (Doppler frequency shift is directly related to the radial velocity), and frequency level is represented by the color of the traces. Each spectral slice (or cross-section) of



(a)



(b)

Figure 2. (a) Square wave signal from the sound wave (inset) and the harmonic spectrum of the sound wave, (b) Balmer series spectrum of hydrogen atom emission showing emitted lights from electrons, excited to different levels ($n = 3,4,5,\ldots$), dropping back to $n = 2$.

the spectrogram lines corresponds to a single frequency spectrum calculated from data of a time frame as shown in the conceptual illustrations of the spectrogram in figure 3.

The colour scale of the spectrogram shows levels of frequency, with red being higher and blue lower.

Using this spectrogram for demonstrating the Doppler shift of the buzzer's rotation, we found that the shift frequency curve was sinusoidal. When the buzzer reached a position half-way toward the microphone of the iPad mini, the frequency shift reached a maximum value, and when the buzzer receded to the opposite direction the frequency shift decreased until it reached its minimum at the position half-way away in its opposite rotation. A radial velocity of zero occurred at the positions closest and farthest from the detector.

We also discussed at length with students the effects of the orbital period of the star wobble on the frequency variation. Comparing the curves of part I and part IV of figures 3(a), they found that the shorter period of the buzzer's rotation (the star wobble) produced higher maxima of Doppler frequency shift than the longer period.

From working with students we learned that, to clearly demonstrate Doppler frequency shift, we should select the fundamental frequency of the buzzer sound. With the observer (i.e. microphone of the iPad mini) being at rest, the relationship between f and f_n (nth harmonic frequency produced by the buzzer at rest) is given by the Doppler effect equation for a rotating source:

$$f(t) = \left(\frac{v_s}{v_s + 2\pi f_b R \sin(2\pi f_b t)}\right) f_n$$

Where v_s is the velocity of sound, R the orbital radius and f_b is the frequency of rotation of the buzzer, respectively. From this equation we obtained good results from our demonstration. For example, in the case of the maximum variation in velocity, where the buzzer is located at 90 degree angle to the detector, given $R = 0.2$ m, $v_s = 346$ m s^{-1}, $f_1 = 3.914$ kHz and $f_2 = 7.855$ kHz, the calculated result for the maximum fundamental frequency of 3.932 kHz with the buzzer rotating at a speed of 75 rev min^{-1} and that for the 2nd harmonic of 7.903 kHz at 100 rev min^{-1} agree with the experimental values of 3.937 kHz and 7.906 kHz by the above equations; the small differences in the resulting frequency are due to slight deviation from the set rotation speed. The 1st order

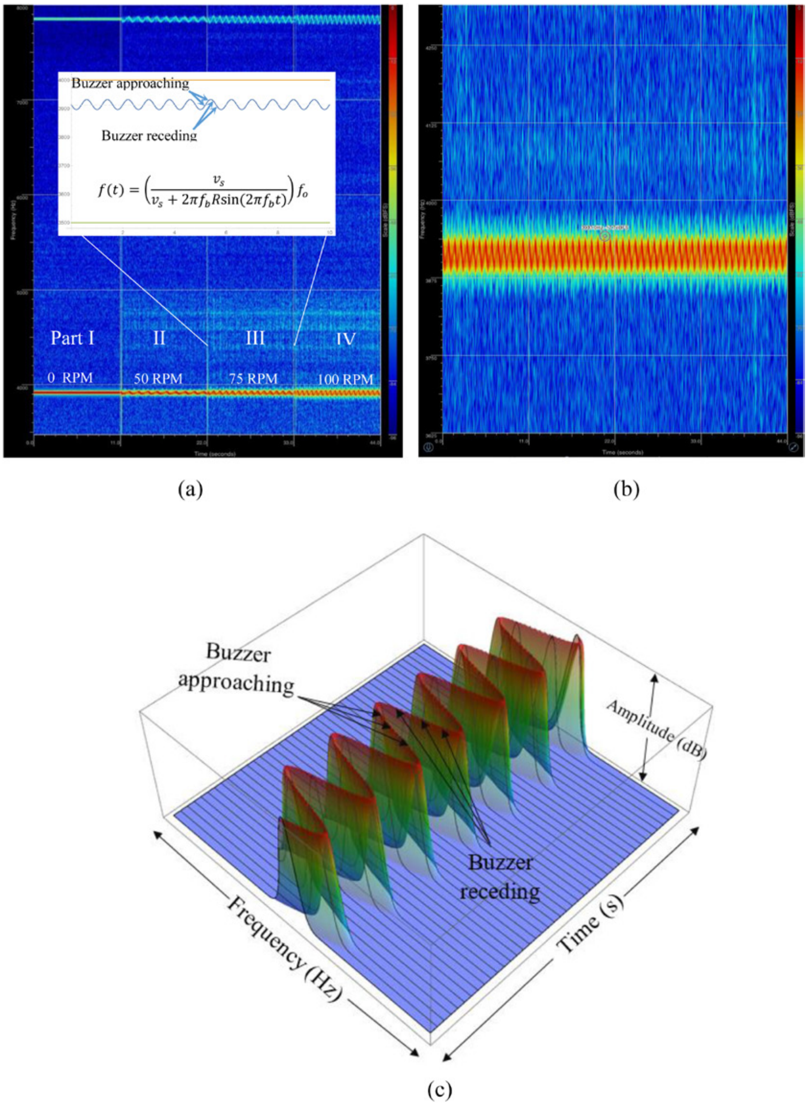


Figure 3. (a) Experimental data showing of frequency variation at different rotation speeds, (b) a magnified picture of the frame of 75 RPM rotation and (c) conceptual illustration of the spectrogram emphasizing frequency change as the buzzer is approaching and receding relative to the detector.

frequency increase of the buzzer sound by 23 Hz from $\Delta f_1(t) = f_1 - f(t)$ indicates a blueshift.

$$v_b(t) = v_s\left(\frac{f_n - f(t)}{f(t)}\right) = \frac{\Delta f_n(t)}{f(t)} v_s$$

In the case of the rotating buzzer having the radial velocity of v_b, the classical Doppler shift for sound travelling with velocity v_b (much less than the speed of light c) is given by the expression

$$v_b = \pm \frac{\Delta f}{f} v_s$$

where the positive sign is for the buzzer moving toward the observer (detector) and the negative sign for it moving away from the observer. To obtain the Doppler effect of emitted light from a star, the relationship has to be modified to involve the Lorentz transformation. For example, in the flat space-time, this Doppler shift includes the relativistic effect of time dilation, the star's clock runs slower from the view of the observer when it is receding. To transform relativistically, the observed frequency is modified by the factor $\sqrt{c - v/c + v}$ for the receding star. In determining the radial velocity of the star wobble by observation of the red and blue shift of spectral lines, it is convenient to express the Doppler effect in terms of the shift in frequency compared to the resting frequency of the star. In special relativity, which describes physics in the flat space-time, if the star wobble emits light with frequency f_0, the radial velocity of the star wobble is given by the expression

$$v = \pm \frac{\Delta f}{f_c} c$$

where the positive and negative signs are taken from observation of the red and blue shift of spectral lines of star wobble and f_c is the rest frequency of light. When we compare the formula of the frequency shift of light and sound, we find that the structure of the sound Doppler shift formula is similar to that of the light's Doppler shift. We realise that the Doppler shift for light depends only on the velocity of the emitter relative to that of the receiver; however, for sound, the shift depends on the velocities of both of them relative to air. In our case the detector is static thus air does not affect our results, i.e. we can use the characteristics of the frequency shift of sound to simulate radial velocity detection by light frequency shift.

Acknowledgment

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Appendix

Converting Doppler shift to radial speed

To detect the characteristics of a star wobble, the star's velocity variation can be determined by analysis of frequency shifting of the star's spectral lines of the Balmer series which leads to the idenitification of the radial speed of the star's wobble as shown in figure A1. The relativistic Doppler shift can be measured by the change in frequency of spectral lines based on the radial velocity of the wobbling star relative to the receiver and the rest frequency of star:

$$v = \frac{\Delta f}{f} c \tag{A.1}$$

Where v is the radial velocity of the star wobble relative to the receiver in m s^{-1} and c is the speed of light in m s^{-1}.

Determining exoplanet properties with radial velocities

Radial velocity measurement depends on a spectroscopic method for finding exoplanets. It involves the observation of Doppler shift in the spectrum of a star that mutually rotates with the planet under detection. Periodic variations in the star's spectrum can be detected with the frequency of characteristic spectral lines increasing and decreasing regularly over a period of time. These variations are indicative of the radial velocity of the star being altered by the presence of the planet mutually orbiting the star, causing Doppler shift in the light emitted by the star. The star's radial velocity curve, as shown in figure A1, gives information for finding the exoplanet's mass and orbital radius.

The orbital period of the star (P_{star}) comes directly from the observed period of Doppler shift in the spectrum of the star around which the planet orbits. Knowing a star's temperature, the mass of the star (M_{star}) can be calculated using the relationship between mass and luminosity of the star. But for calculating the combined mass, that of the exoplanet can be approximated as zero because its mass is so much smaller than that of the star. Using Kepler's third law of planetary motion, the observed period of the star (equal to the period of the observed variation in the star's spectrum) can be used to determine the planet's distance from the star (r) using by equation below:

$$r = \left(\frac{GM_{star}}{4\pi^2}\right)^{1/3} P_{star}^{2/3} \tag{A.2}$$

where G is the gravitational constant.

The orbital speed of the exoplanet can be determined using the circumference of the orbit divided by the orbital period as given by:

$$V_{planet} = \frac{2\pi r}{P} = \left(\frac{2\pi GM_{star}}{P}\right)^{1/3} \tag{A.3}$$

Where V_{planet} is the exoplanet's orbital speed.

When the exoplanet is orbiting the parent star, total momentum of all the objects in the system

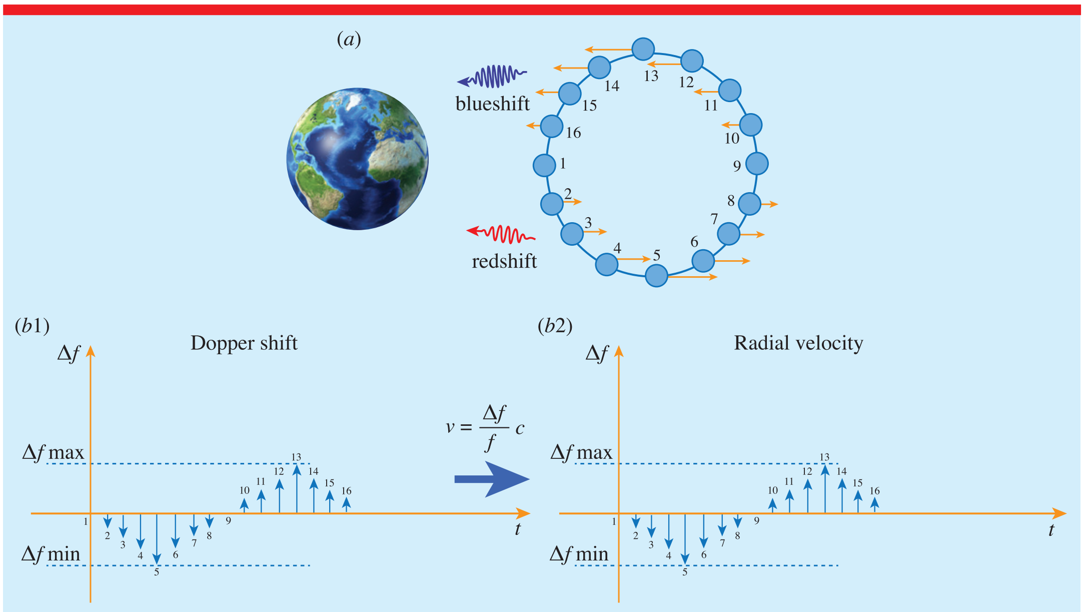

Figure A1. Relationship between Doppler shift and radial speed (a) cyclic movement of the buzzer (star) relative to the detector (on earth), (b1) frequency shift versus rest frequency level and (b2) radial velocity change versus rest frequency. Numbers in (a) and (b1), (b2) show the corresponding positions of the buzzer.

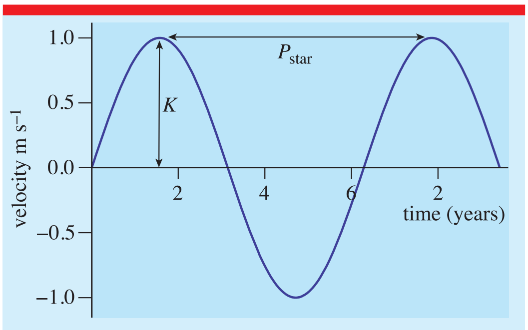

Figure A2. The periodic shifts in radial velocity using Doppler spectroscopy [6].

cannot change because of the conservation of momentum. The exoplanet's mass, M_{planet}, can be determined from the radial speed ($V_{star} = K/\sin\theta$) of the exoplanet.

$$M_{planet}V_{planet} = M_{star}V_{star}$$

$$M_{planet} = \frac{M_{star}V_{star}}{V_{planet}} \quad (A.4)$$

where θ is the inclination of the planet's orbit to the line-of-sight.

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References

[1] Jenkins J M *et al* 2015 Discovery and validation of Kepler-452b: a 1.6 R⊕ super earth exoplanet in the habitable zone of a G2 star *Astron. J.* **150** 56
[2] George S J 2011 Extrasolar planets in the classroom *Phys. Educ.* **46** 403–6
[3] LoPresto M C and McKay R 2005 An introductory physics exercise using real extrasolar planet data *Phys. Educ.* **40** 46–50
[4] Prather E E and Slater T F 2001 Bringing extra-solar planets into the introductory physics classroom *Phys. Teach.* **39** 120–2
[5] Cowley M and Hughes S 2014 Characterization of transiting exoplanets by way of differential photometry *Phys. Educ.* **49** 293–8
[6] Choopan W *et al* 2011 A Demonstration setup to simulate detection of planets outside the solar system *Phys. Educ.* **46** 554–8
[7] Kereszturi A 2013 How to size an exoplanet? A model approach for visualization *Astrobiol. Outreach* **1** 1–5
[8] Morse J A, Mathieu R D and Levine S E 1991 The measurement of precise radial velocities of early type stars *Astron. J.* **101** 1495–510

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