Lenses

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I. INTRODUCTION

To explore lenses and their phenomena, we used a laser, converging and diverging lenses, a Galilean and a Keplerian telescope and measured focal lengths and angular magnification. In addition, we used a converging lens to verify the thin lens equation. We also constructed a makeshift lens to investigate spherical aberration and the circle of least confusion.

II. THEORETICAL BACKGROUND

Rays, approximations of electromagnetic waves in the visible spectrum, traveling through a dielectric material causes the electrons within the material to oscillate and produce an electric field which alters the wavelength of the incident light. [1] [2] This effect is known as refraction and the ratio of the wavelength of the light outside the dielectric to the wavelength inside is given by

$$n = \frac{\lambda_0}{\lambda} \tag{1}$$

When a beam encounters a discontinuity in the index of refraction, the direction of this ray is changed. The refracted wave is given by

$$n_1 sin\theta_1 = n_2 sin\theta_2, \tag{2}$$

known as Snell's law of refraction. [1]

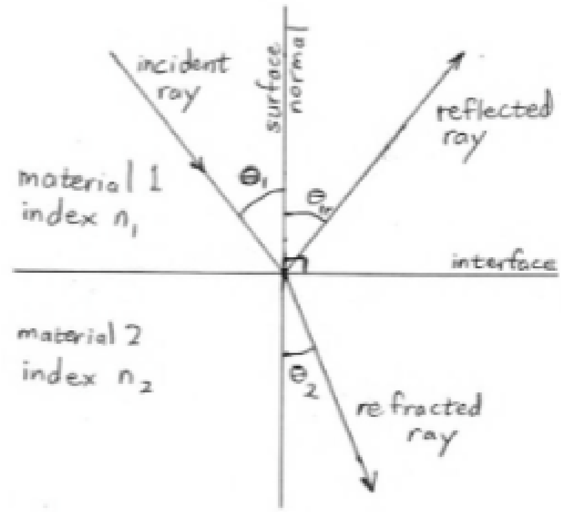

FIG. 1. Behavior of light at refractive index discontinuity [1]

Lenses make use of refraction by bending light emitted from a point source to seem as though it is coming from a different location, called the image plane. [3] If the rays incident upon a lens are parallel, the distance to the image is called the focal length.

A useful technique to determine where the image plane is located is called ray tracing, which is simplified by the thin lens approximation. This approximation assumes that a ray incident upon the lens enters and exits the lens at the same distance from the optical axis. [3] The thin lens equation is given by

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}, \tag{3}$$

where f is the focal length, s is the distance between the object and the lens, and s' is the lens-image distance. [3]

The focal length of a spherical lens made of material with refractive index n in a vacuum is given by the lens makers equation, denoted

$$\frac{1}{f} = (n-1)[\frac{1}{R_1} - \frac{1}{R_2}], \tag{4}$$

where R_1 and R_2 are the radii of curvature of the sides of the lens. [3]

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A. Aberration

Since the index of refraction is frequency dependent, lenses effectively have different focal lengths for varying wavelengths, which produces a rainbow edge around objects. [3]

Spherical aberration refers to different foci of rays incident upon a spherical lens at varying positions. [3] The point where the variation in refracted beams is at a minimum is called the circle of least confusion.

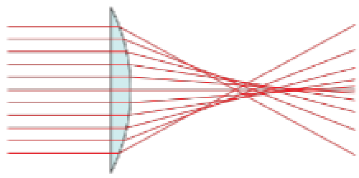

FIG. 2. Spherical Aberration: the circle of least confusion is the point where the light rays are most narrow [3]

B. Telescopes

A Galilean telescope expands a section of sky by bringing parallel rays of a point light source to a focus using a convergent objective lens, and then intercepting them and rendering them parallel again using a divergent lens. This results in no intermediate focus and thus the image is not inverted.

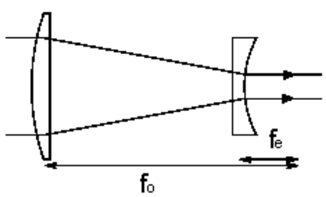

FIG. 3. Galilean Telescope [4]

A Keplerian telescope is similar to a Galilean telescope, but instead employs a convex second lens, resulting in inverted emerging light rays that are convergent and allowing for a larger field of view.

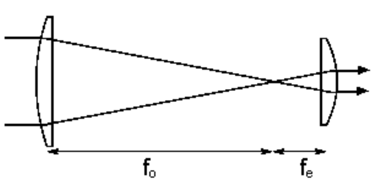

FIG. 4. Keplerian Telescope [4]

The angular magnification m, the ratio of the angle of the outgoing rays to the angle of the incoming rays, for both types of telescopes is given by

$$m = \frac{\theta_o}{\theta_i} = -\frac{f_1}{f_2}. \tag{5}$$

The distance d between the two lenses for both type of telescope is given by

$$d = f_1 + f_2. \tag{6}$$

III. EXPERIMENTAL PROCEDURE

A. Focal Length and Spherical Aberration of Lens

We began by creating a holder for our laser pen but cutting holes in two pieces of foam board large enough for the laser to fit into and fixing these into a wooden block with slits. We then selected a transparent bottle and filled it with water to function as our lens. We created two foam stands to ensure the beam from the laser was the only light incident upon our lens. We next focused the laser beam upon our lens, and recorded the deflected beam to determine the focal length and circle of least confusion.

B. Focal Lengths of Two Converging Lenses

We first created two holders for our lenses by using a craft knife to cut a circular hole roughly the size of the lens in a foam board.

We then chose two converging lenses and placed them in our holders. Using our laser, we checked the focal length of each lens individually. We then verified the thin lens equation using one of the lenses.

C. Angular Magnification of Keplerian Telescope

We then used our measured focal lengths of the two converging lenses to create a Keplerian telescope. We then measured the angular magnification of our Keplerian telescope. We determined the angular magnification by placing a foam board in front of the telescope and inserting sewing pins into the board to mark distances of a ruler viewed through the telescope, shown in figure 6.

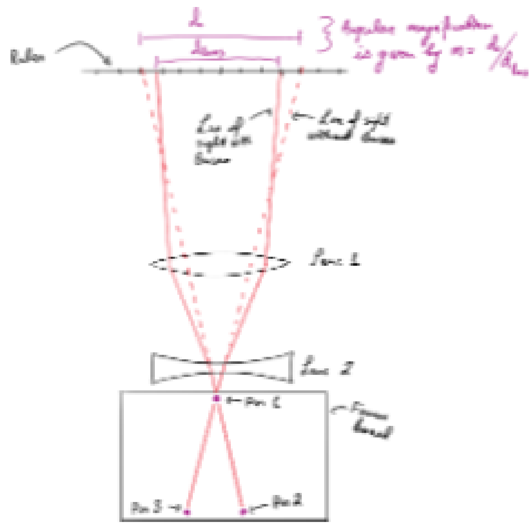

FIG. 5. Measurement of Angular Magnification of Galilean Telescope [3]

D. Focal Length of Diverging Lens

We next selected a diverging lens and constructed a Galilean telescope. After determining the separation necessary for the telescope, we inferred the focal length of the diverging lens.

E. Angular Magnification of Galilean Telescope

We used the same procedure as with the Keplerian telescope to determine the Galilean telescope's angular magnification.

IV. CONCLUSION

A systematic error in this experiment is that we neglected the diameter of our eye, which has a minimal effect on the values measured. [3]

The disagreement of our focal length with the prediction from the thin lens equation is due in part to our lens not being spherical. Our lens was also not in a vacuum, so this is a source of systematic error for this measurement as well. [3]

Issues in this experiment could have arisen due to measurement error. The uncertainty in these measurements could also be reduced by using a measuring device with greater precision than the centimeter scale we employed. [5]

[1] D. Heinzen, Refraction of light, (2020).
[2] G. C. King, *Vibrations and Waves*, 1st ed. (Wiley, 2009).
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[7] R. P. Feynman, *The Feynman Lectures on Physics*, Vol. 3 (Addison Wesley, 1971).