

# Inferior Mirage Simulation with an Ethanol-Water Interface

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## Abstract

A positive refractive index gradient at an ethanol/water interface in a small glass tank models similar positive refractive index gradients created by a layer of warm air above a calm sea. Inferior mirages (omega and hourglass sunsets) are simulated and photographed as the interface slowly diffuses. Island mirages, made with small silhouettes placed in the tank, complete the simulation of an inferior mirage sunset seen in the atmosphere.

**Keywords:** inferior mirages, ethanol-water interface, positive refractive index gradient

## I. INTRODUCTION

Mirrored cars over dry asphalt, upside-down cargo ships, and omega sunsets are neither hallucinations nor products of our outlandish imaginations. Instead, these are the result of a physical phenomenon called a mirage.

A mirage is due to refraction in a non-uniform medium (air) and is categorized to be either inferior or superior. The wet road effect, often seen when driving on hot days, is an example of an inferior mirage. Figure 1 shows a dramatic example of this effect in a video on the web taken at the airport in Christchurch, New Zealand.<sup>1</sup> The inverted virtual image of the plane in Figure 1 is perceived as a reflection of the plane on a wet runway when the runway is actually dry.



**Figure 1.** An inferior mirage at Christchurch Airport, New Zealand.<sup>1</sup>

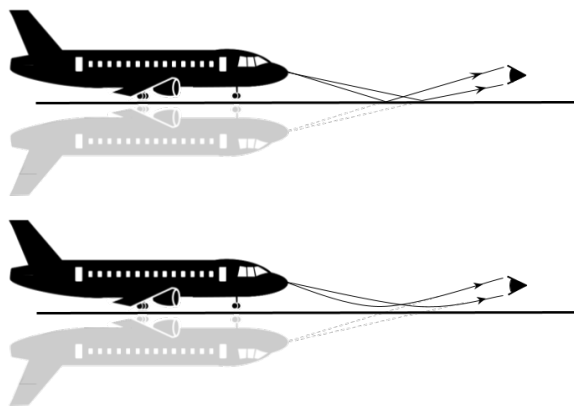
The refractive index gradients responsible for creating the strange visual spectacle of mirages, namely sunset and island inferior mirages, will be studied here.

## Inferior Mirages

Inferior mirages like that shown in Figure 1 require a medium that has a positive vertical refractive index gradient (increasing refractive index with increasing height).<sup>2</sup> Under these conditions, an inverted virtual image is observed below the object.

Light rays refract towards regions with a greater refractive index. In a positive vertical refractive index gradient, the rays refract upwards, creating the curved paths shown in Figure 2. The light appears to be coming from below the ground for the observer, forming an inverted virtual image below the object.

Sunlight warms the tarmac on a hot day, which in turn warms a layer of air right above it. This results in an increase in air density with height and a positive vertical refractive index gradient. As shown in Figure 2, this leads to the formation of an inverted virtual image known as an inferior mirage. Positive refractive index gradients in the atmosphere are unstable because warm air, being less dense, will rise into cooler air above, causing the mirage to shimmer as seen in the video from which Figure 1 was taken.



**Figure 2.** Ray paths from a point on an airplane to the eye of an observer, reflected by a plane mirror (top) and refracted in a positive vertical refractive index gradient that effectively acts like a mirror (bottom). The diagrams cannot be drawn to scale due to the long horizontal path length with angles of incidence above the tarmac that approach  $90^\circ$ .

An inferior mirage is sometimes seen over the sea under calm conditions on a warm afternoon. The effect gives the impression that distant islands are undercut at a false horizon formed by the ‘reflection’ of the sky. In an extreme case, an island can appear to be floating above the sea. Figure 3 is based on an image taken on a warm calm afternoon from a balcony 40 meters above the beach at Jomtien, Thailand.<sup>3</sup> Distant islands are undercut and appear to float above false horizons. The mirage obscures the actual, more distant horizon. The islands and a closer boat appear to be reflected at their own false horizons indicated by horizontal black lines.

### Superior Mirages

Superior mirages (not simulated in this work) are formed by vertical negative refractive index gradients (decreasing refractive index with increasing height). In this instance, light refracts on downward curving paths to an observer who is usually below the active layer.

Negative refractive index gradients form in the atmosphere when layers of warm air overlay cooler, more dense air. These gradients are relatively stable, can occur at any height, and may involve multiple layers. Depending on the number of layers present, the distance to the object, and the height of the



**Figure 3.** Inferior mirages in the Gulf of Thailand off Jomtien Beach.<sup>3</sup>

observer, a superior mirage is formed with one or more upright and/or inverted images above the object.

Superior mirages can be simulated with brine and freshwater layers in a glass tank because brine is denser than water and has a greater refractive index. Inferior mirage simulations with vertical positive refractive index gradients in a tank are less common and are the subject of this study.

### Simulations of Inferior Mirages

A mirage in the atmosphere is formed over a long optical path with very small refractive index changes. Simulations are possible on a small scale with a short path length, provided that the refractive index varies sufficiently with height.

A stable positive refractive index gradient needed for an inferior mirage can be achieved with ethanol and water. At  $20^\circ\text{C}$ , ethanol ( $0.789\text{ g/ml}$ ) is less dense than water ( $0.998\text{g/ml}$ ). Additionally, the refractive index of ethanol at  $20^\circ\text{C}$  is  $1.362$ , significantly greater than that of water ( $1.333$ ). So, when ethanol is layered carefully over water, a sharp interface is created at a density discontinuity. The steep refractive index gradient formed as diffusion mixes the layers allows simulations of inferior mirages with a path length as short as  $15\text{ cm}$ .

### Omega Sunsets

The most common inferior mirage sunset is named after the Greek letter omega, which it resembles. The flattened disc of the setting sun appears to sit on a bright shallow upturned basin directly on the horizon. Like all inferior mirages, the omega sunset is caused by a positive refractive index gradient. During the day, the ocean can warm up the air just above it while the air higher up cools. A positive



**Figure 4.** A typical omega sunset image.<sup>4</sup>

refractive index gradient is created that increases in steepness as one approaches the ocean's surface. As a result, the observer sees an inverted image below the actual sun, as seen in Figure 4. The inverted image is mostly obstructed by the ocean, creating the base of the omega shape.

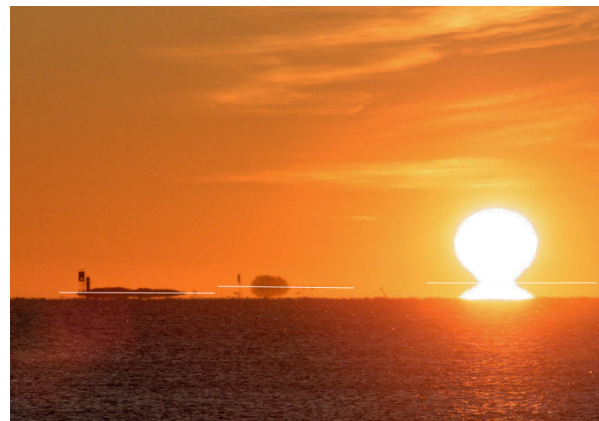
### Hourglass Sunsets

Figure 5 shows what is referred to as an hourglass sunset and mirage islands over the sea off the coast of Helsinki.<sup>5</sup> Like the omega sunset, the hourglass sunset mirage is caused by a positive refractive index gradient as the sun is setting.

### Island Mirages

The inferior mirage effect can be observed with islands. In Figure 5, two islands are observed "floating" above the horizon. They appear to float because of severe undercutting by the mirage effect. The junction where the top and bottom image of each island meet is marked with a white line. The right-hand island has a slightly higher junction than the left-hand island. This is likely due to the island being farther away from the observer than the island on the left.

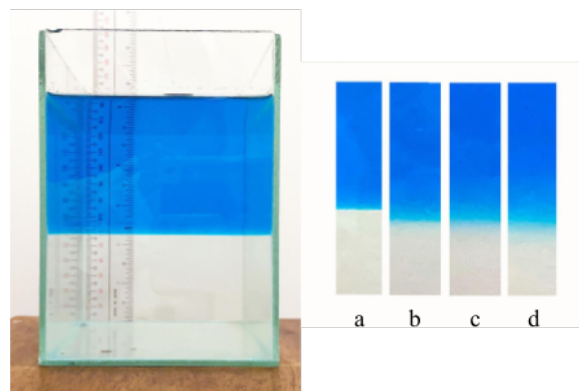
Here we will simulate sunset and island mirages by using an alcohol-water interface created in a glass tank. The procedures for simulating the various inferior mirages described here can be used in special exhibitions or lectures.



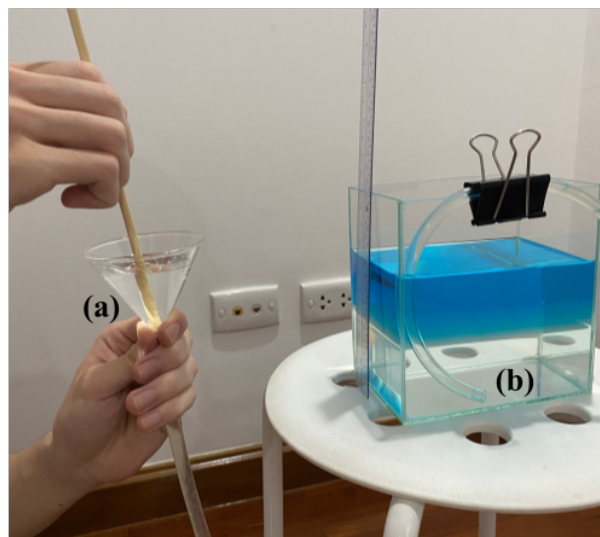
**Figure 5.** Hourglass sunset and island mirages.<sup>5</sup>

## II. METHODS

A small rectangular glass tank with dimensions of 10x15x15 cm (width x length x height) was used. Tap water and a 70% ethanol solution with blue dye added were used for all the simulations. The ethanol solution, produced by Alsoff, is available in pharmacies in Bangkok. The refractive index of a water/ethanol mixture increases steadily up to 70% ethanol and reaches a maximum of 1.3612 at 76%. Using pure ethanol would not have been an advantage. The blue dye provided two benefits: increasing diffusion near the initial interface could be visually observed over time (Figure 6), and the complementary color of blue can be orange or yellow, depending on the shade of blue. So, when a



**Figure 6.** Ethanol solution layered over tap water. The right panels show diffusion at the interface progressing after 0(a), 5(b), 8(c), and 12(d) hours.



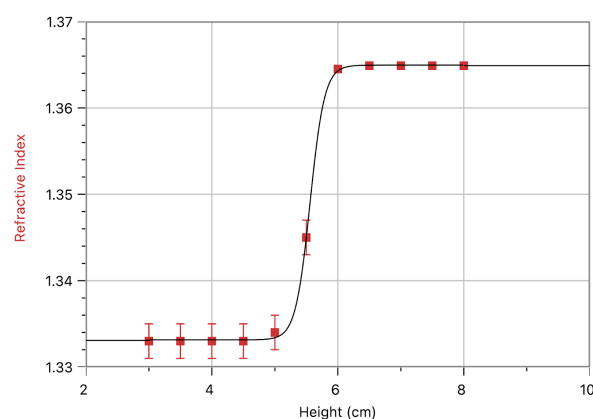
**Figure 7.** The setup for adding water underneath ethanol.

dark blue prop sun is photographed in the blue ethanol solution, the complement of the color image will be a yellow prop sun in orange ethanol, the colors of sunsets.

The tank was filled to a depth of 6.0 cm with the 70% ethanol solution and kept away from direct sunlight in an air-conditioned room at 25°C. Tap water was slowly introduced to the bottom of the tank to lift the alcohol using a tube and a funnel. To do this, water was first run through the tube. The tube was then blocked at one end ((a) in Figure 7) before the other end was slowly lowered to the bottom of the tank ((b) in Figure 7). The blocked end was then slowly opened to allow water to flow into the bottom of the tank. The current was kept at a minimum and frequent observations were made to ensure no significant mixing occurred at the interface. After the ethanol level reached 13.0 cm, a smaller tube was used to siphon off 1.0 cm at the height of 6.5 cm to sharpen the interface and remove any unwanted irregularities created during the lifting process.

### Refractive Index Gradients

The refractive index gradient across the height of the tank was determined by collecting samples at height intervals of 0.5 cm after diffusion had proceeded for 0, 5, 8, and 12 hours. A plastic pipette was slowly lowered into the tank, disturbing the gradient as little as possible. A small sample of 2-3 drops was collected at each height and tested for ethanol concentration with an automatic temperature compensation (ATC) alcohol refractometer that

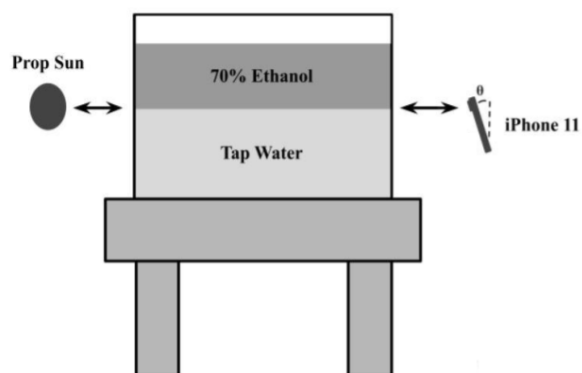


**Figure 8.** The steep refractive index gradient one hour after the ethanol solution was layered over tap water in the tank.

measures ethanol concentrations from 0% to 80%. In Figure 8, refractive index is graphed against height to reflect the refractive index gradient within the tank (measured ethanol concentrations were converted to refractive index).<sup>6</sup>

Images were recorded with an iPhone 11 back-facing camera. The height of the camera and distance to the tank were noted for all mirage photographs. The angle of the camera was measured using the IOS built-in Measure app. A dark blue disc with a diameter of 3.0 cm was printed as a prop sun. Making a negative of the image produced a simulated yellow sun in an orange sky.

After a sharp interface was created, the iPhone camera was positioned to take photographs through the tank with a path length in the gradient of 15 cm, as shown in Figure 9. The camera was 30 cm from the near side of the tank, and the phone was angled



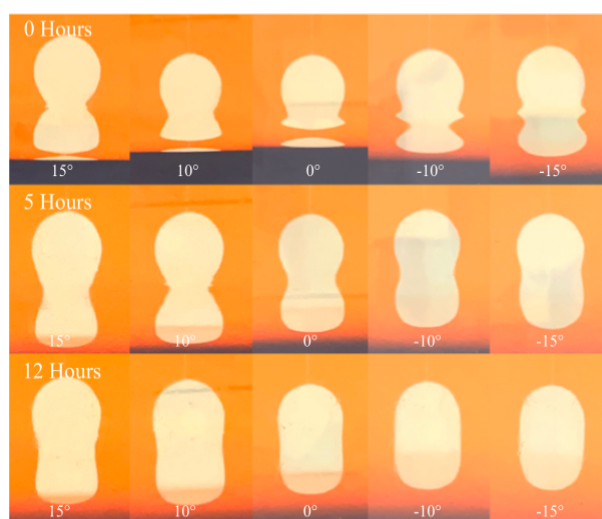
**Figure 9.** Schematic diagram of the experimental setup.



at  $0^\circ$  to the vertical. The height of the camera was set at the height of the interface. Burst photos were taken at 10 fps while the blue disc was slowly lowered against the back of the tank. With the same camera distance, photographs were taken at heights of 2 cm and 4 cm above and below the height of the interface with camera angles of  $\pm 10^\circ$  and  $\pm 15^\circ$ , respectively. This procedure was repeated three times with the same method, and images were taken in the same way for each run to ensure that the results were consistent and reproducible.

### III. RESULTS AND DISCUSSION

The refractive index gradient in the tank creates a non-uniform cylindrical lens with a horizontal axis. Animations compiled from the burst images show the effects for different camera positions with respect to the interface for different gradients. Because the refractive index gradient that produces an inferior mirage is always a warm layer of air close to the ground or the sea (Figure 2), inferior mirages are always observed from above and close to the gradient. Superior mirages (not simulated in this paper) are produced by gradient layers higher in the atmosphere and can be observed from below or above the optically active layer. Figure 10 shows selected images for the full range of camera positions for completeness, but the sunset simulations that follow were made with the camera positioned just above the level of the optically active layer.



**Figure 10.** Selected negative color images of mirages at different times and various camera angles (from left to right:  $15^\circ$ ,  $10^\circ$ ,  $0^\circ$ ,  $-10^\circ$ ,  $-15^\circ$ ).

A smaller angle will increase the flattening effect until the bottom image cannot be seen when the camera is exactly level with the interface (difficult to achieve due to the camera's size and the requirement of a perfectly clean interface with no mixing of ethanol and water).

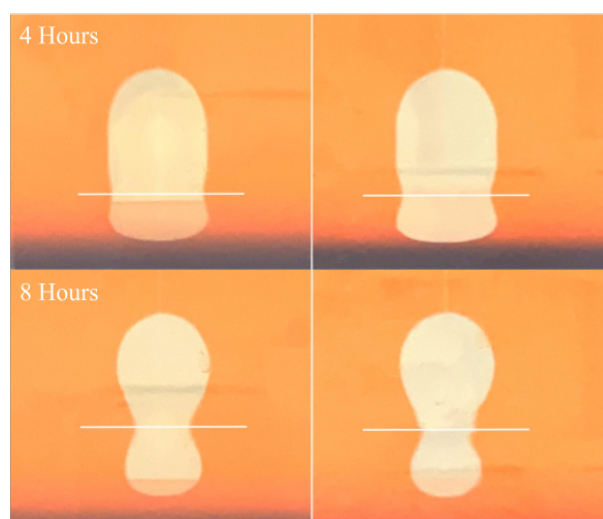
#### Mirage Effects

Images of mirage effects were taken. The refractive index gradient was measured at 0, 5, 8, and 12 hours after creating the interface. Images were recorded with the camera positioned slightly above the height of the interface. Figure 11 shows two pairs of images taken on different days with different interfaces created for each day. What is seen depends on diffusion time and camera position but is consistent within close limits from one trial to the next.

In Figure 11, the images taken during different runs on different days all have stretched upper portions and inverted bottoms, which taper to meet at a false horizon. The upper image of each pair has a rounded top. The bottom inverted images are flattened because of the camera position above the interface.

#### Omega Sunset Simulation

Shortly after overlaying water with the alcohol solution, the iPhone camera lens was positioned slightly above the interface level at a distance of 26 cm from the near-side of the tank. The phone was angled at  $0^\circ$  to the vertical, and the blue disc was



**Figure 11.** Comparison of mirage effects taken 4 and 8 hours after the creation of the interface and on different days (camera angle of  $0^\circ$ ).

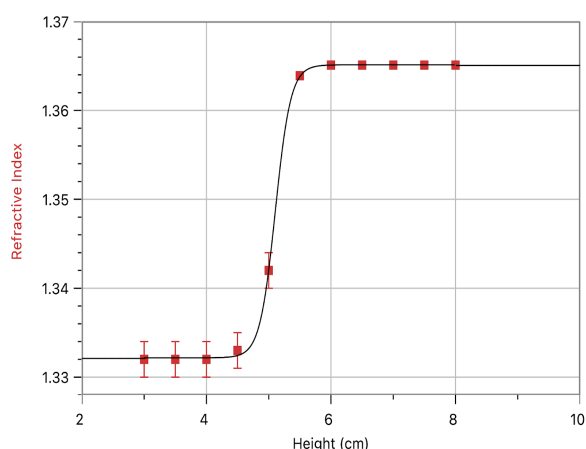


**Figure 12.** Simulation on the left and an actual omega sunset on the right.

lowered against the glass until the lower edge was 1 mm below the interface. The mirage image is shown in Figure 12 (left), next to an image of a real omega sunset.

A horizontal red line shows the apparent joint between the upright and inverted images. Firstly, no obvious vertical stretching is observed in the simulation because there was minimal diffusion between the ethanol and water interface, as seen on the refractive index versus depth plot in Figure 13. Comparing the simulation with the real sunset, the two images are almost identical except that the simulated omega sunset does not show the marked compression of the upper disc along the vertical axis.

The apparent progressive flattening of the sun's disc (or full moon) as it approaches the horizon occurs at all times, regardless of the presence of an inferior mirage. This can be clearly seen in the composite image in Figure 14 showing the sun in three subsequent positions over the sea at Jomtien on the Gulf of Thailand.



**Figure 13.** Refractive index gradient in the tank when the image in Figure 11 was taken.

The flattening of the sun that occurs with or without a mirage, and is first noticeable when the sun is still some two degrees above the horizon, shows that disc flattening is not a local effect in the atmosphere but occurs over a very long path length and at greater heights. The effect is due to a general universal reduction in refractive index because of reducing pressure and air density with altitude. Because light rays from the bottom of the solar disc (closer to the horizon) are refracted on downward curving paths to a greater extent than rays from the top of the disc, the result is a vertically compressed image of the sun (Figure 14). This flattening is not observed in the tank.<sup>7</sup>

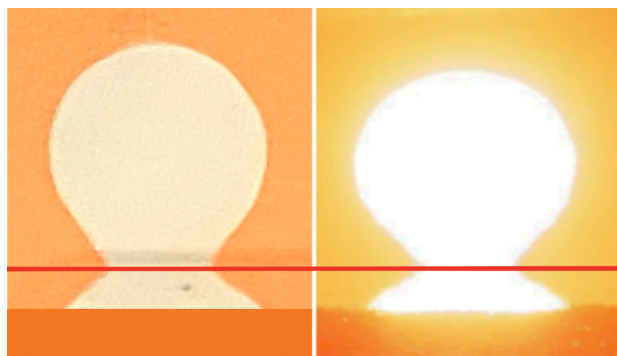
### Hourglass Sunset Simulation

To simulate an hourglass sunset, the alcohol/water interface was allowed to diffuse at 25° C for four hours. The camera was positioned just above the height of the less well-defined interface and at an angle of 0° to the vertical. The distance to the near-side of the glass was 31cm, and the prop sun was lowered to be 1 to 2 cm above the interface. The height was adjusted to match the reference photo.

In the simulation, the inverted basin below the disc is deeper than that of an omega sunset. The waist where the two images run together is higher above the false horizon and is narrowed. There is some vertical stretching of the lower half of the upper disc, but the rounded top is largely unaffected. Both images are shown side by side for comparison in Figure 15.



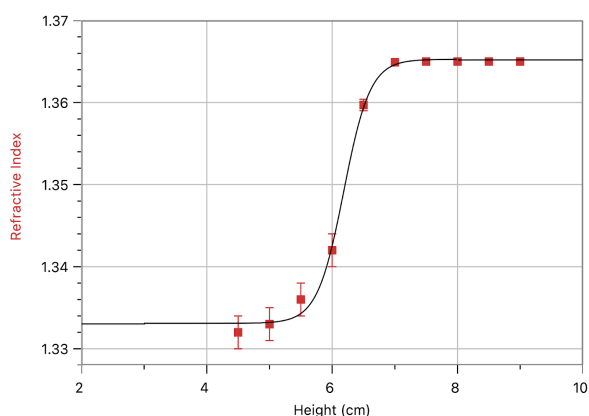
**Figure 14.** The sun appears to flatten as it approaches the horizon over the sea in Jomtien.<sup>7</sup>



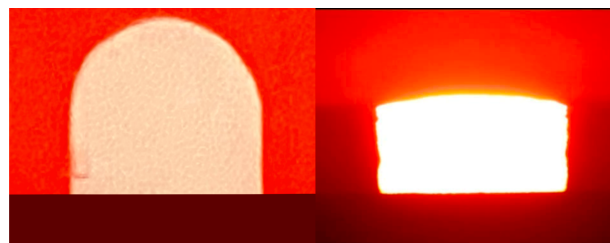
**Figure 15.** A simulated hourglass sunset (left) and the same phenomenon in the atmosphere (right).

Both images have the shape of an hourglass: a circular upper and lower body that tapers off in the middle to form a neck (the junction). The bottom image is partially blocked by a false horizon in the real hourglass sunset, leaving only the upper portion of the bottom image visible. A matching false horizon has been added to the image on the left.

The tapering effect towards the neck is caused by the positive refractive index gradient, which vertically stretches the top and bottom images of the sun. This can also be seen in the real sunset, suggesting that the hourglass sunset simulated in the tank is formed by a similar positive refractive index gradient responsible for hourglass sunsets in the atmosphere. The refractive index gradient can be seen in Figure 17.



**Figure 17.** Refractive index versus depth after four hours in the tank in the tank that simulates the hourglass sunset.

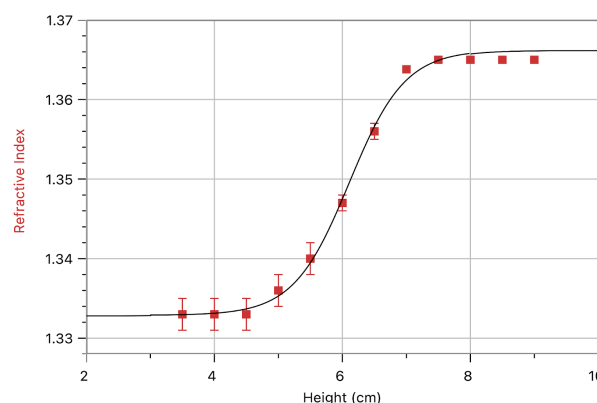


**Figure 16.** A failed attempt to simulate a square sunset with a negative refractive index gradient.<sup>8</sup>

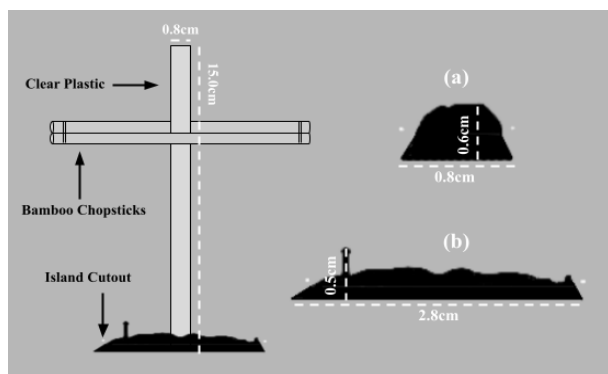
### Square Sunset simulation

Following the successful simulation of the omega and hourglass form of an inferior mirage sunset, it was thought that it might be possible to simulate the third recognized sunset mirage. This so-called square sun has a distinctive flat top. The gradient was allowed to diffuse for eight and twelve hours, and attempts were made over three days. The best effort is shown in Figure 16 with an image from the web for comparison. The refractive index gradient when the image in Figure 16 was taken can be seen in Figure 18.

The failed simulation in Figure 17 does have a square section above the horizon, but it has a high rounded top which is nothing like the image of Zinkova's sunset on the right.<sup>8</sup> Square sunsets, which are infrequent and seldom photographed, appear to be due to a superior mirage in a positive refractive index gradient. Note what looks to be perhaps three vertically compressed images on the right in Figure 16, a typical form of a superior mirage. This question could be pursued in a subsequent paper.



**Figure 18.** Refractive index versus depth in the tank for the simulation in Figure 17.

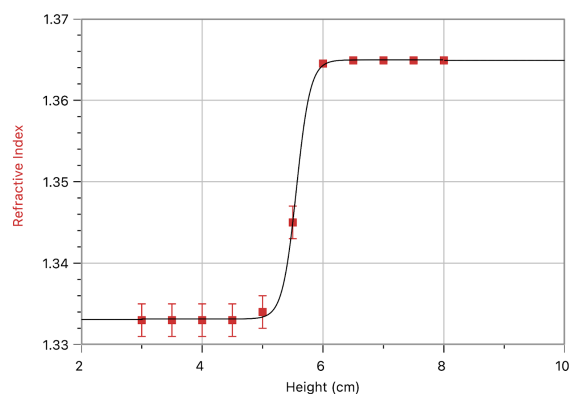


**Figure 19.** Dimensions of templates used to simulate island mirages.

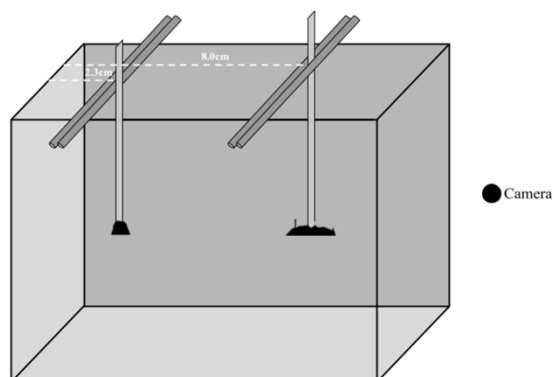
### Island Mirage Simulations

To simulate the phenomenon of island mirages, silhouettes of each island in Figure 6 were printed and laminated. The bottom of the long island print (island (b) in Figure 19) was extended so that the island printout measured 0.5 cm from the top of the chimney-like protrusion to the bottom and 2.8 cm in width. For the squarish island print (island (a) in Figure 19), its bottom was also extended so that the printout measured 0.6 cm in height and 0.8 cm in width. The island prints were fixed to clear plastic strips 0.8 cm wide and 15 cm long. The plastic strips were clamped to bamboo chopsticks, and the island cutouts were hung in the tank close to the interface. This setup allowed for repositioning just above the interface.

Figure 20 is a schematic diagram of the island cutouts in the tank at different distances from the camera. Final vertical adjustments with respect to the interface were made by eye. The camera was



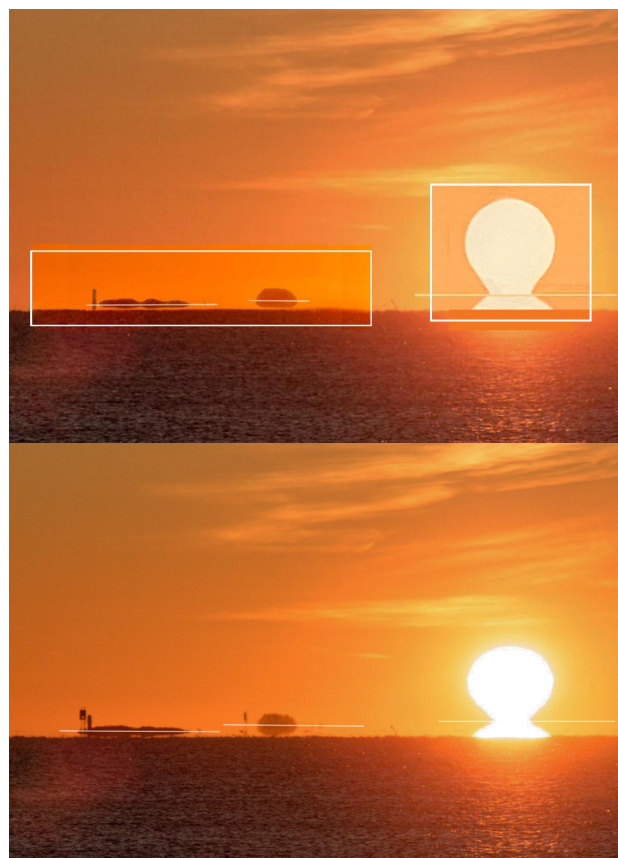
**Figure 21.** Refractive index versus depth in the tank for the simulation in Figure 22.



**Figure 20.** Diagram of the island mirage simulation setup.

angled at  $0^\circ$ , 0.6 cm above the interface, 36 cm from the near side of the tank. The island mirage was simulated in the refractive index gradient shown in Figure 21.

The mirage simulations match in all details except the failure to show a flattened disc in the tank for the reasons noted previously.



**Figure 22.** Images of the island and hourglass mirage simulations (top) pasted to Figure 5 (bottom).



The results from this study have shown that omega sunsets, hourglass sunsets, and island mirages can be successfully simulated with positive refractive index gradients created by layering ethanol on top of water in a glass tank. The gradients in the tank are on a different scale but similar to the refractive index gradients responsible for the same types of mirages in the atmosphere.

#### IV. CONCLUSION

Ethanol was layered on top of water to create positive refractive index gradients. This allowed successful simulations of the omega sunset, hourglass sunset, and island mirages. The omega sunset and island mirage simulations required a steep positive refractive index gradient, while the hourglass sunset simulation required more gradual increases in refractive index with increasing height. These simulations with simple apparatus could be used for an exhibition or a special lecture if a tank was carefully positioned, filled, and allowed to settle before the event.

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#### Acknowledgements

I would like to express my thanks for permission to use images from the web that are, in each case, referenced to the originals.