Mirages above the sea waters

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Abstract
This paper, which has teaching and public-science aims, presents some examples, attained in the Southern Bays of Galicia (Spain) of inferior and superior mirages, including castles in the air, fata Morganas and towering. The explanation for the unusual atmospheric refraction is presented, and the different kinds of ray paths distortions that lead to each optical effect and the respective gradient indexes that generate these distortions are shown. In addition, the temperature differences required for each case are related to the successive oceanographic and climatic conditions that occur along the year in this coast.

1. Introduction
The temperature difference between the sea surface and the atmosphere can give rise, in stable weather conditions, to a continuous vertical variation of the density in the lowest air layers. The gradient index so established causes the bending of the light rays that, coming from an object, form its image in the observer’s eye. This effect produces the so called mirages, in which the images of objects such as boats, rocks or small islands are seen, for an observer not very high over the sea level, transformed in stunning, unreal-like and often beautiful ways.

Although there are descriptions of mirages since the Classical Antiquity, the first scientific explanation was given by Gaspard Monge, who accompanied Napoleon Bonaparte in the Egypt campaign (see, for instance, web1). The word mirage has been defined in different ways (see web2 and web3), we will consider here that mirages are optical phenomena, in which images of objects are seen displaced and/or distorted respect their normal appearance, and whose cause is the bending of light rays passing through atmospheric air layers with a gradient refraction index. Given the fact that the conditions to the observation of these phenomena are not very common, they are termed “unusual refraction”, which does not mean that the normal refraction laws have any fail or singularity here. When these unusual images are displaced upwards they are called superior mirages, and when this displacement is downwards, inferior mirages (for a more comprehensive classification of the mirages see Minnaert, 1993: 59-74, Lynch and Livingston, 2001: 54-62, or web2). For instance, the Fig. 1 shows a rocky small island seen under a Fata Morgana and Fig. 2 its normal appearance.
Figure 1. The small island of Rúa seen under a Fata Morgana effect. The sail boat in the red frame appears duplicated with a superior and inverted image. It can be noticed also a vertical compression of the lighthouse.

Figure 2. The same island of the Arosa Bay in its normal appearance.

The pictures here presented were taken in the Southern Bays of Galicia, the northwest region of Spain, under different oceanographic and climatic conditions, both in summer and winter days. The relationship between these conditions and each kind of mirage is discussed in this paper.

2. Optical explanation
The explanation of these effects lies in the light refraction phenomenon. When a ray passes from a zone with a given refraction index to another with a different one, undertakes a change in its propagation direction. It is illustrated in Fig. 3, where the angle change is given by the Snell Law. If the index variation is continuous (i.e., a gradient index exists) the change of the propagation direction is also gradual and the ray path describes a curve.

Figure 3. Direction change of a ray that passes through decreasing index layers.
This ray curvature can be observed when a laser beam (for example that of a laser pointer) is made pass through a variable concentration dissolution. In Fig. 4, a layer of sugar was deposited in the bottom of a transparent recipient and subsequently an amount of water was added without messing up the sugar layer. As the sugar starts to dissolve in the water, a vertical variation in the concentration appears, such that it decreases with height. In optical terms, a gradient is established depending only on the height and in which the refraction index decreases with it (hence, horizontal planes of equal index). It is important to note in Fig. 4 that the laser beam bends towards the area where the index is higher, i.e., the concave side of the curve is facing to the increasing index, as it is shown also in the diagram of the Fig. 3.

Figure 4. A laser beam is bent downwards when passes through a variable-concentration dissolution (in this case, decreasing upwards).

3. Inferior mirages
Those where the refraction index increases with height and, hence, the rays are bent upwards, are termed inferior mirages. The widest known of them are that seen in the desert, and many people observed some of them looking along a road in a hot sunny day. In the sea they occur when the temperature of the water is higher than that of the air, so air layers close to the sea surface have lower refraction index than those away from it. This condition is typical of the autumn and winter season, when the air cools down quicker than sea water since this has a larger thermal inertia.

Figure 5. Ray paths for an inferior mirage. *g.l.*: the gradient index layer; *l.l.*: limiting line; *v.l.*: vanishing line.
Fig. 5 is a diagram where the ray paths are shown for this case. Rays coming directly from a couple of points in the object arrive to the observer, but other rays from the same points, with different initial directions, reach also the observer because they suffer a curvature in the gradient index area. To arrive at the same point, via the same horizontal plane, these two rays have to cross each other and, therefore, the observer sees a second image of the object, inverted and below the direct one, like reflected in a horizontal mirror. Nevertheless, this reflection is not perfect: the curved rays arrive with an angle between them slightly smaller than that of the direct ones and hence the inverted image appears compressed vertically. The vanishing line (v.l.) is the horizontal “mirror” plane, and below it no rays from the object reach the observer, so this part of it is not seen. The rays from points above the limiting line (l.l.) reach the observer position only directly and hence they are not affected by the mirage.

**Figure 6.** The Port of Villagarcía seen under an inferior mirage in a calm winter day. The red line is the vanishing one.

Fig. 6 is a picture of a port seen under an inferior mirage, and the red line is the v.l. for this case. It was taken in a winter day with a weak breeze, when the water temperature was between 9 and 10 °C and that of the air was between 5 and 6 °C; the distance to the object was 8 km and the height of the camera over the sea surface was approximately 2 m.

**Figure 7.** The Cies Island, in the Vigo Bay (autumn). The wider red line is the v.l., the narrower one is the l.l. and inside the red frame an effect of *castle in the air* is observed.
In Fig. 7, both the vanishing and the limiting lines are drawn. Inside the rectangular frame a curious effect can be seen: the rocks in this part seems to be on air above the water surface, something like a cantilever. It happens when the object’s height is lower than that of the limiting line, then part of the sky over it is seen below and the object seems to float in the air. This effect is called *castle in the air* and is an inferior mirage.

4. Superior mirages

When the sea water is colder than the atmosphere, the temperature in the air layers close the sea surface increases with height, that is, in higher planes it is higher than in lower ones. This temperature distribution is called a *thermal inversion* and, hence, the refraction index decreases with height, the same that happens in the dissolution of the Fig. 4. In this case, light rays from objects are curved like the laser beam in this picture, i.e., they are bending downward (Fig. 8), and the optical effects so originated are termed *superior mirages*.

This temperature inversion is rather usual all along the summer in the Southern Galician Bays, and is caused by the upwelling phenomenon. In this season, the Azores High moves northeast and, given its clockwise rotation, causes northeast winds in the Spanish northwest coasts. These winds blows from land to sea in the Southern Bays. In this way, they drag the superficial water layers out of the bays, which are substituted by abyssal waters, since the continental shelf is not very wide here. The vertical stream so formed merges close to the bays, and in the case of the Arosa one, deeper than the others, inside it. This is the so called upwelling. These depth waters are very clear, have many minerals in dissolution (that feed the rich submarine ecosystems of the region) and are considerably cold (specially for swimming purposes). When the wind calms, a thermal inversion air layer is formed in contact to the sea surface, and this is the cause for the superior mirages that following are described (for a more detailed description of the upwelling phenomenon see Varela and Rosón, 2008: 14-18).

Fig. 1 is an example of a mirage of this kind: the water temperature was between 12 and 14 ºC, that of the air between 27 and 30 ºC, the distance to the object was 6 km and the camera was 2 m high over the sea surface. It was taken in a calm summer day. Probably the most curious effect here is that suffered by the small sail boat inside the red frame: it can be seen above it a second image of itself but inverted, like a reflection around a horizontal plane slightly above the boat.

![Figure 8. Rays paths for a superior mirage](image)

This image-inversion effect, that can also affects rocks, island and other objects, is called sometimes *Fata Morgana*, since this is the traditional name for it in the Messina Strait, between the Italian Peninsula and the Sicilian Island, where it seems to be rather often. The explanation for it is
given in the diagram of the Fig. 8. The abnormal curvature of the ray paths caused by the variation of the refraction index of the air, leads to the formation of an image above that of the real object and the inversion is due to the crossing of the rays coming from point at different heights as the figure shows. Moreover, these curved rays arrive to the observer with an angle between them lower than if they were direct, and this causes a vertical compression of the upper image, like it happens with the image of the lighthouse in Fig. 1. The inversion line (i.l.) is sometimes lower than the top of the object and, hence, the inverted image is seen overlapped partially over the real one.

![Figure 9](image)

**Figure 9.** Towering effect. Relatively low rocks seen as columns or towers. (Small island of Sagres, Arosa Bay, summer).

Another effect that can be seen in Fig. 1 and, even clearer, in Fig. 9 is that known as *towering*. It consists in that the image of an object is seen elongated, and also defocused, vertically. In Fig. 9 rocks no very prominent are seen like towers and walls, high over the sea surface (in fact, Galician sailors said that the coast was *encastillada* or *amurallada*). Even many people interpreted this as remote and fantastic towns. The explanation is given in Fig. 10: a set of rays coming from the same point can arrive to the observer in directions slightly different, so forming virtual images displaced vertically.

![Figure 10](image)

**Figure 10.** Vertical elongation of a point: formation of towers or walls. The same can occur in inferior mirages but with the rays curved on contrary sense.

In fact, this effect can appear simultaneously with the former one, being both overlapped, as can be seen in Fig. 1. The same superposition is given in Fig. 11, that is the rock on the left hand side of Fig. 9: this rock is *towered* by vertical elongation and, at the same time, by the presence of a superior and inverted image of it.
Figure 11. Superposition of the vertical elongating effect with the superior inversion one.

Really, this elongating or *towering* effect can appear also in inferior mirages, overlapped, for example, with a *castle in the air*.

It is important to note that these effects are strongly dependent on the height of the observer over the sea surface. The authors of this article have observed that an intense effect of towering, observed standing on the beach, close to the water edge (eyes less than 2 m high), was very weak, and even disappear, when viewed from nearby rocks, about 4 m high. It seemed that in this case the gradient index layer was pretty thin, less than 6 m.

Conclusions
This paper describes different kind of mirages that can be seen in the sea. The explanation of each one is given in a way easy to understand for a public without specific optical knowledge. A set of pictures of mirages in the Southern Galician Bays is presented and data about the conditions they were taken are provided. Each one is analyzed to identify the different optical effects that produce the respective image, since more than one effect can occur simultaneously. In addition, some of the different oceanographic and meteorological conditions that occur in this coast in each season of the year are described, and related to the temperature gradients that, in turn, produce each mirage.

References
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