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# Why Are Water-Seeking Insects Not Attracted by Mirages? The Polarization Pattern of Mirages

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The polarization patterns of an imaginary water surface – a mirage – and a real water surface – the sea – were recorded by video polarimetry at North African desert and coastal sites, respectively. Although a mirage appears as a shiny water surface for any brightness- and colour-sensitive visual system such as the human one, the polarization characteristics of mirages differ completely from those of water surfaces. A computational analysis based on digitized polarization data shows that a mirage does not alter the polarizational state of mirrored light, while light reflected from the water surface is polarized more or less horizontally. Since water insects detect water by means of the horizontally polarized reflection of light, these animals – unlike humans – cannot be visually deceived by and attracted to water-mimicking mirages.

Mirages occurring on roads on hot days is a well-known phenomenon: there appears to be a pool of water in the distance, but it dissolves on approach. The sky, various landmarks, and objects are mirrored in this 'pool'. Such mirages are also seen on hot plains. To the human visual system a mirage appears as a shiny water surface, and humans are optically deceived by it. In addition, the chaotic vibration of a mirage due to the turbulent flows of hot air imitates the wind-generated undulation of a water surface. Water insects, however, do not detect water on the basis of its brightness and colour but by means of the horizontal polarization of reflected light [2, 6–8]. The question therefore arises as to whether mirages can also deceive water-seeking insects. To answer this question the polarization characteristics of a mirage and a real water surface were recorded, computationally analysed and compared with each other.

A mirage was studied on a sunny hot day under clear sky conditions on 3 August 1996 in the Tunisian desert (within the salt pan of the Chott-el-Djerid; distance to Tozeur: 22 km, distance to Kebili: 70 km). As at the study site the Chott-el-Djerid was totally arid, a beautiful mirage could be observed near the horizon. The polarization patterns of the mirage and the landscape were measured by video polarimetry (for methods see [3]). In addition, the reflection-polarization pattern of the surface of a sea was measured by video polarimetry on a sunny warm day under clear sky on 9 August 1996 on the beach of Maharès (Tunisia). Both the mirage and the sea were seen near the horizon at a great distance from the observer. Thus the direction of view of the video-camera recorder was always almost horizontal.

The range of the angle of incidence of rays of light involved in the formation of a mirage was estimated in order to compare quantitatively the polarization of light mirrored and reflected by the mirage and the flat water surface. Rays of light started from the typical height of 1.5 m of an observer towards the hot desert ground with different angles of observation $\beta$ (Fig. 4A). The air column between the observer and the ground was divided into a variety of unit layers. Applying the Snellius-Descartes law of refraction at the interface of two adjacent layers, the trajectories of the rays were calculated (ray tracing, Fig. 4A). The temperature and refractive index of any given layer was taken as constant. The temperature profile of the air above the ground was modelled by an exponential function $t(h)$ (Fig. 4B), the parameters of which were fitted on the basis of the data presented in [9]. Using this profile, the distribution of the refractive index $n$ of air was calculated as a function of height $h$. The change in $n$ versus $t$ is given in [5]. In the case of unpolarized incident light the degree of polarization of light reflected from the flat water surface was calculated by the use of the Fresnel laws for reflection [1].

Row 1 of Fig. 1 provides a view of a salt-pan landscape, the Chott-el-Djerid in southern Tunisia, over which a mirage has developed. The top half of the landscape is covered by clear sky. The darker, cone-shaped band in the middle part of the picture is a mountain (the height of which decreases gradually from right to left) and its mirage. Below the mountain the

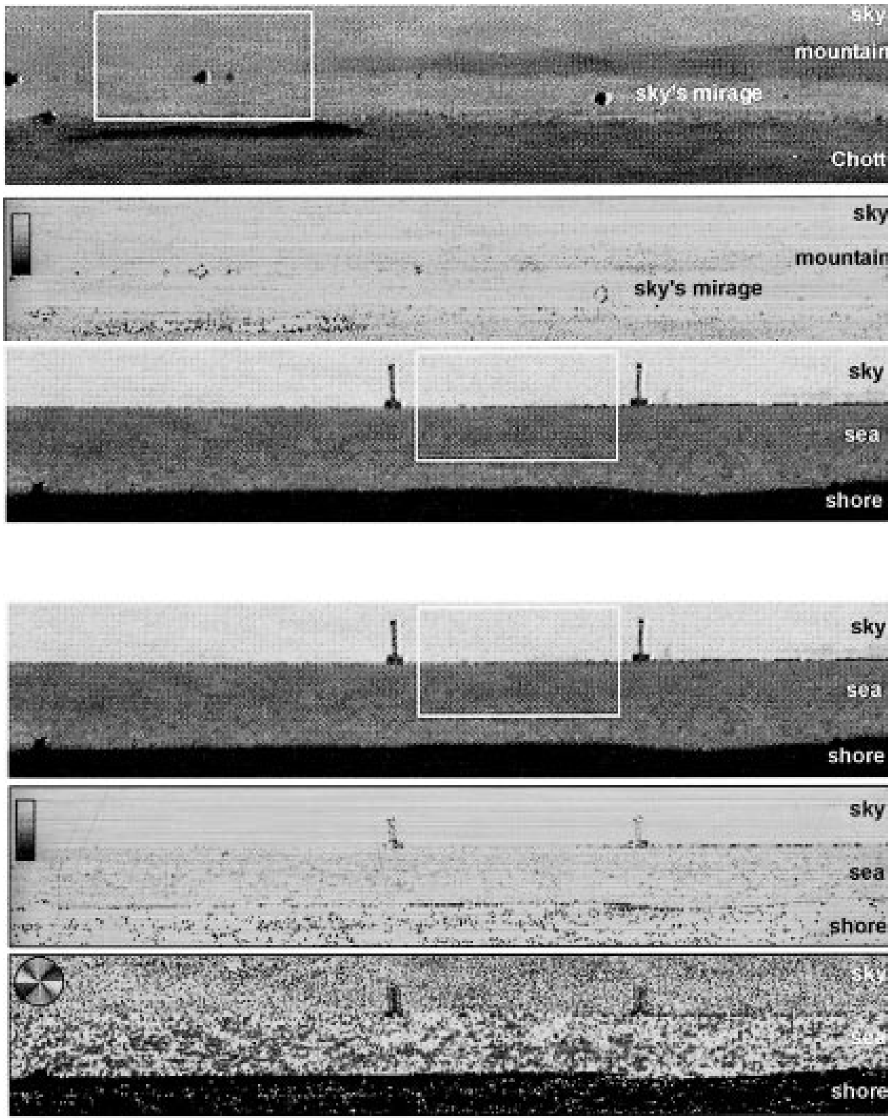


Fig. 1. *First row*, colour picture of a mirage occurring above an inland (desert) landscape, the Chott-el-Djerid in southern Tunisia. The dark cone-shaped band at the middle right is a mountain (tapering off to the left). Below the mountain the shiny stripe represents the mirage of the sky which merges in the real sky on the left. The lower half of the picture is occupied by the sandy floor of the chott. The vertical angular extension of the landscape shown is about 1.5°. *Second, third rows*, spatial distribution (false-colour maps) of the degree (δ) and the direction (*α*) of polarization of the landscape portrayed in the first row and measured through the green channel of the video polarimeter. *Fourth – sixth rows*, same as the first three rows, but now for a seaside landscape (near Maharès, Tunisia). The uppermost part of the picture is filled with clear skylight. The middle part is occupied by the sea, the lowermost part by the shore. Different numerical values of δ and *α* are depicted by different shades and hues of colour: (i) The higher the degree of polarization, *the darker is the shade of blue* (*bright blue*: $\delta = 0\%$, *black*: $\delta = 100\%$). (ii) *The darker the red and yellow*, the more deviates the orientation of the E-vector from the vertical (*red*: $0° \leq \alpha < 45°$, *yellow*: $135° \leq \alpha \leq 180°$). *The darker the green and violet*, the more the orientation of the E-vector deviates from the horizontal (*green*: $45° \leq \alpha < 90°$, *violet*: $90° \leq \alpha < 135°$). In the representations of E-vector orientation (*third, sixth rows*) *black* represents unpolarized light ($\delta = 0\%$). *Small rectangular areas* (*first, fourth rows*), the regions for which the histograms of the direction and degree of polarization are given in Fig. 2

shiny, water-mimicking region is the sky's mirage merging into the sky on the left side. Note that as the mirror effect of a mirage is optically equivalent to the total reflection of light, the horizontal area of the sky's mirage appears as bright as the sky itself. Thus, due to the mirage of the sky the mountain seems to be elevated above the apparent horizon, i.e. above the sandy bottom of the chott.

The two rows of pictures shown underneath represent false-colour images of the spatial distributions of the degree (row 2) and direction (row 3) of polarization occurring within the same areas of the landscape. The sandy bottom of the chott is slightly polarized, as is the light reflected by the mountain. The light emanating from the sky is partially polarized ($\delta_{\text{average}} \approx 15\%$) with an E-vector alignment of about 120° (as measured clockwise from the vertical). As the light from the sky and the sky's mirage coincide in their degree and direction of polarization, no contrast occurs between the sky and its mirage. Figure 2A presents histograms of E-vector orientation and degree of polarization calculated for the small rectangular area outlined in the upper left of row 1 of Fig. 1. This area includes part of the sky and its mirage. As these histograms exhibit only single peaks, there are no differences in the mean direction or degree of polarization between the sky and its mirage.

Rows 4–6 of Fig. 1 provide views (as well as the spatial distributions of the degree and direction of polarization) of another type of landscape, the muddy beach near the village of Maharès in central Tunisia. The top half of the landscape as shown in row 4 is occupied by clear sky. The darker band in the middle represents the sea. Note the undulating surface of the sea and, at the horizon, the two sailing boats with their vertical yards. There is a sharp brightness contrast between the sea and the sky. Similarly sharp contrast lines occur in the maps of the degree and direction of polarization in rows 5 and 6, respectively. The sea surface is partially horizontally polarized with an average degree of polarization of $\delta_{\text{average}} \approx 19\%$. This low degree of polarization is due to the small angle included by the surface of

  

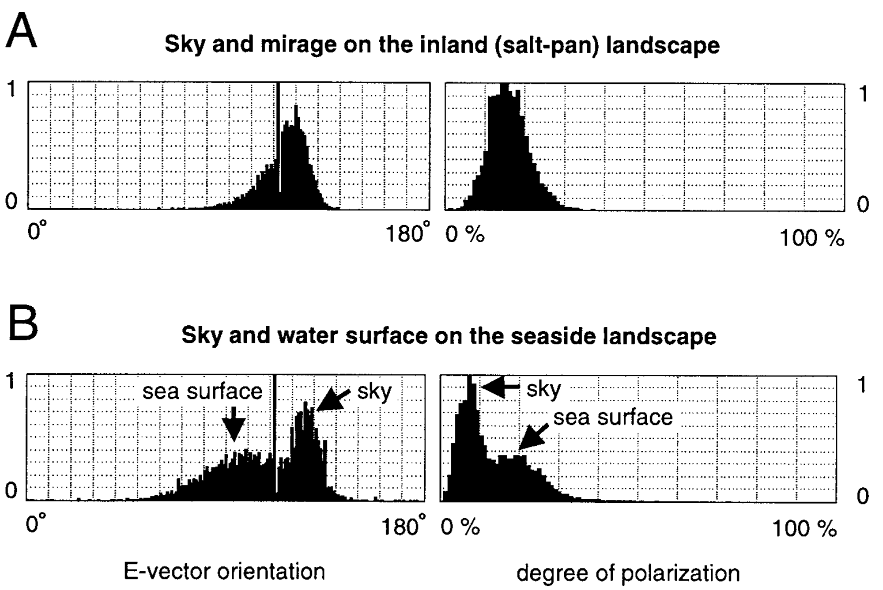


Fig. 2. Histograms (relative frequency) of E-vector orientation (*left*) and degree of polarization (*right*) computed for the rectangular area seen in the first and fourth rows of Fig. 1. A) Mirage occurring above the desert plain of the Chott-el-Djerid. B) Seaside landscape, Maharès

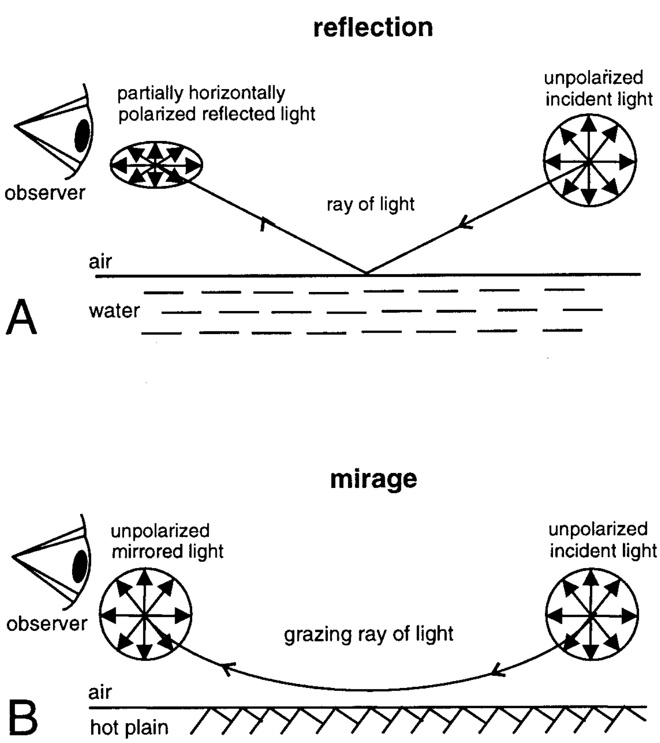


Fig. 3. A) Unpolarized incident light becomes partially horizontally polarized when reflected by water surfaces. B) Formation of a mirage above a hot plain, where the air temperature decreases exponentially as height above ground increases. As a consequence, the refractive index of air increases abruptly with height above ground, and grazing rays of light refract and bend gradually into the eye of the observer. This gradual refraction does not alter the polarization of light; for example, unpolarized incident light remains unpolarized. *Inset figures,* polarization ellipses and E-vector orientations

the sea and the line of sight. The clear sky is partially polarized. At the time of day at which the picture was taken the degree of polarization of the sky near the horizon ($\delta_{\text{average}} \approx 8\%$) was even lower than that of the sea surface. The E-vector orientation in the strip of sky shown here is about 125°. Figure 2B depicts quantitative data about E-vector orientation and degree of polarization as computed for the rectangular area demarcated in the middle part of row 4. In these histograms the double peaks again illustrate the polarization contrast between sky and sea.

The video-polarimetric measurements presented above make it quite clear that there are significant differences between the polarization characteristics of water-imitating mirages and real water surfaces. Water surfaces always reflect more or less horizontally polarized light (Fig. 3A), in which the degree of polarization depends upon the direction of view and the undulation of the surface. If the water surface is far away from the observer, the degree of polarization is relatively low due to the shallow direction of view. If the horizon is defined by the border between the water surface and the sky, there is in general a high polarization contrast between water and sky in both degree and direction of polarization (compare rows 4–6 of Fig. 1). The reason is that due to its reflection from water surfaces skylight becomes repolarized (Fig. 3A).

On the other hand, in the inland landscape there is no contrast at all between the sky and its mirage with respect to brightness, degree of polarization and E-vector orientation (compare rows 1–3 of Fig. 1). Mirages are not real reflections but are formed by gradual refraction of light (Fig. 3B) above hot plains. The nearer to the ground, the warmer is the air and the smaller its index of refraction. Thus the direction of grazing rays of light is gradually changed to such an extent that the rays do not reach the ground but are deflected in an upward direction (Fig. 3B). This gradual deflection provides an observer with the same impression as total reflection does. As such gradual refractions of light do not produce any polarization effects, unpolarized light remains unpolarized

 

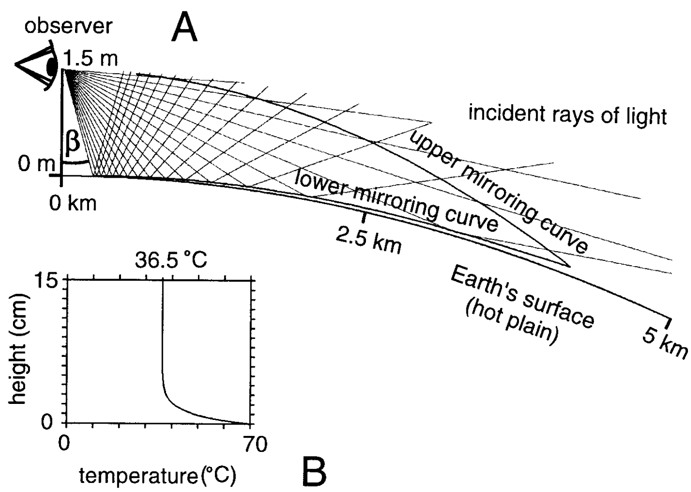


Fig. 4. A) Computed ray tracing of a mirage in a vertical section B) at a given temperature gradient. A) The angle of observation $\beta$ changes from 89.4° up to 90° as measured from the vertical. For the sake of clarity, different scales are used for vertical and horizontal distances. The curvature of the earth's surface is taken into consideration. The so-called 'mirroring curves' are determined by the positions of total light reflection. B) Vertical temperature gradient above a desert sand surface as recorded in [9]

[4]. When polarized rather than unpolarized light is mirrored by a mirage, the degree and direction of polarization are not changed at all [1]. This phenomenon, which can be deduced from Fig. 1 as well (see those parts of rows 2 and 3 in which there is a mirage of a more or less polarized area of the sky), makes mirages optically different from reflections by real water surfaces.

Figure 4A represents the computed ray tracing of a mirage at the temperature gradient depicted in Fig. 4B. The rays that are totally reflected from the 'upper and lower mirroring curves' take part in the formation of the erect and reverted (mirror) images, respectively, of objects perceived by an observer. The angle of incidence of these rays ranges from 89.4° up to 90° (as measured from the vertical). If the incident light is unpolarized, the mirrored light also remains unpolarized. In comparison, if unpolarized incident light is reflected from a flat water surface under angles of incidence larger than 89.4°, the degree of (horizontal) polarization is not larger than about 2% [1]. However, as one approaches the water surface, the horizontal polarization of reflected light increases abruptly. In contrast, a mirage (as a rainbow) can never be reached by an observer, and the angle of observation always remains the same, i.e. nearly 90°.

In contrast to the calculated 2% degree of polarization of the light reflected from a distant, flat water surface, the degree of polarization of the sea surface in Fig. 2B is on average 19%, and reaches maximal values of 40%. The reason for this difference is twofold: on the one hand, the incident skylight is partially polarized (ca. 8%); on the other hand, due to wind influences the sea surface is considerably undulating. Thus the average angle of incidence of skylight reflected from the wavy water surface is smaller than for an ideally flat, exactly horizontal water surface. As the angle of incidence decreases to less than 90°, the degree of polarization of reflected light increases. In the case of unpolarized incident light the observed average and maximum degree of polarization of the reflected light (19% and 40%, respectively) means that the average and minimum angles of incidence are 84° and 77°, respectively.

Schwind [6, 7] has recently demonstrated that water insects detect water surfaces on the basis not of brightness but of polarization cues. Consequently, the polarization-sensitive visual systems of these insects cannot be deceived by a shiny, water-mimicking mirages. Mirages can imitate water surfaces only for those animals whose visual systems are polarization blind, but sensitive to brightness and colour differences. A polarization-sensitive water-seeking insect is able to detect the polarization characteristics of a mirage. Since these characteristics differ considerably from those of real water surfaces, these animals cannot be deceived by and attracted to mirages.

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