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DO BROWN PELICANS MISTAKE ASPHALT ROADS FOR WATER IN DESERTS?

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Recently, brown pelicans (*Pelecanus occidentalis*) have been observed to crash on roads in Arizona. It was hypothesized that the pelicans have mistaken the heat-induced shimmer of the asphalt surface for lakes. Here we propose two counter-arguments for this proposition: (i) The edge of a mirage can never be reached, because it continuously moves away when the observer tries to approach it. (ii) We show by computation that the edge of the mirage from a landing brown pelican is so distant that the bird cannot reach it by gliding, even if the edge did not move off, independently of the beginning height of gliding. Consequently, the brown pelicans should have known at the moment of decision for landing that they could not reach the distant shimmering part of the asphalt road by gliding, and thus they would be forced to land on the asphalt. If the dry asphalt surface is smooth enough, the reflection of sunlight from the asphalt could deceive water-seeking flying pelicans, which is explained in detail here. Another explanation could be that brown pelicans may not be "intelligent" enough to grasp that they can never reach the continuously moving off shiny distant part of an asphalt road.

Key words: brown pelican, *Pelecanus occidentalis*, desert, asphalt road, mirage, visual deception

INTRODUCTION

PITZL (2004) reported that brown pelicans (*Pelecanus occidentalis*) have crashed onto asphalt sidewalks and roads in Arizona (USA). The birds have been found from Yuma to Phoenix, and most have been located in southern Arizona, where they have landed while flying out of the Sea of Cortez. The Wildlife Center of the Arizona Game and Fish Department (WCAGFD) has treated the injured pelicans mostly for dehydration and emaciation, but one bird had to be euthanized because its wing was so badly mangled.

According to the officials of WCAGFD, due to a maximum of bird births in 2004 the brown pelicans might have experienced a food shortage along the West Coast and flew far afield to Arizona whilst looking for fish. According to Sandy Cate (from WCAGFD), the observed brown pelicans tried to land on the water, but it was an asphalt surface resulting in a crash. It was hypothesized that the pelicans might have mistaken the heat-induced shimmer of the asphalt surface for lakes and creeks

(PITZL 2004). A report (http://maryjo.pitzl.arizonarepublic.com, http://azgfd.com/artman/publish/article_110.shtml), for example, explained the peculiar phenomenon as follows: "The Sun's reflection, mixed with hot and cool layers of air creates mirages, and the birds mistake smooth pavements for water".

At first sight the hypothesis, that the brown pelicans observed in the Arizona desert were visually deceived by the mirage above hot asphalt surfaces, seems trivial and logical. However, here we show that a more sophisticated explanation is needed. A mirage (like e.g. a rainbow) can be never reached, because it moves off a moving observer. This raises the following question: Did the water-seeking flying brown pelicans not experience that the water-imitating mirage above the asphalt road was moving away as they tried to reach it? This paradox could be resolved with the assumption that the exhausted, dehydrated and emaciated brown pelicans could not fly further in the hot Arizona desert and they had to land onto that distant part of the asphalt road, where the shimmer was visible, in spite of the fact that the edge of the mirage always moved away. The decision for landing by gliding may be made by a brown pelican at a critical minimum height h_{min} of its eyes above the asphalt road. From this critical height there is no return: if a bird began to land from height h_{min}, due to exhaustion its gliding cannot be interrupted in order to take flight again. After the decision for landing a brown pelican could hope to reach the water-mimicking mirage only if the horizontal distance x_E (h_{min}) of the apparent edge E of the mirage was not larger than the distance d (h_{min}) necessary to land by gliding from height h_{min}. The aim of this work is to investigate whether the condition $x_E (h_{min}) \leq d (h_{min})$ could be satisfied in the case of a brown pelican gliding above a hot asphalt surface.

MATERIALS AND METHODS

The tracing of the ray of light taking part in the formation of the apparent edge E of the mirage (Fig. 1) above a horizontal, hot asphalt surface viewed by an observer with eyes at height h_{obs} was computed in the following way: The air column between the observer and the asphalt surface was divided into N = 50 000 elementary layers with a thickness $\Delta h = h_{obs}/N$. Applying the Snellius-Descartes law of refraction $\sin\beta_i / \sin\beta_{i+1} = n_{i+1} / n_i$ at the interface of two adjacent, i-th and (i+1)-th elementary air layers, the trajectory of the ray was computed (Fig. 1). The temperature and refractive index within each elementary air layer was assumed to be constant. The air temperature profile above the asphalt surface was described by the exponential function $T(h,H) = T_{min} + (T_{max} - T_{min}) \times \exp(-h/H)$, where h is the height from the asphalt and H is the characteristic height of the temperature profile, T_{min} = 30 °C (a typical daytime air temperature in a desert high above the ground) and T_{max} is the maximal air temperature immediately above the asphalt surface. In our computations the typical T_{max}-values of 40, 50, 60 and 70 °C were assumed. According to the temperature data measured by WEHNER (1989) in Tunisia, H ranges from 1 to 10 mm. Using the temperature profile T(h,H), the refractive index n[T(h,H)] of air was calculated as $n(T) = 1 + (n_0 - 1) / (\tau \times T + 1)$, where the temperature

T is measured in °C, $\tau = 0.00367$ °C^{-1} is the thermal expansion coefficient of air, and $n_0 = 1.000292$ is the refractive index of air at T = 20 °C and pressure p = 10^5 Pa (LANDOLT & BÖRNSTEIN, 1923).

The path of the incident ray of light propagating toward the hot asphalt surface gradually bends due to continuous refraction (Fig. 1) within the hot air layer above the asphalt. The ray-path returns at a turning point *P* (Fig. 1) and propagates toward the observer *O* (pelican in Fig. 1). The returned ray-path between *P* and *O* determining the apparent edge *E* of the mirage (Fig. 1) was computed from point *P* at which the ray is totally reflected with the critical angle $ß^* = \arcsin(n_1 / n_2)$ determined by the refractive indices n_1 and n_2 of the lowermost (1st) and the next (2nd) elementary air layer above the hot asphalt surface.

RESULTS

Figure 1 shows the schematic tracing of the ray of light taking part in the formation of the apparent edge *E* of the mirage above the horizontal hot asphalt surface viewed by a gliding pelican with eyes at height h_{obs}. The exponential decrease of the air temperature T(h,H) from T_{max} to T_{min} with increasing *h* is shown in the left inset of Fig. 1. Due to this exponential change, T(h,H) practically approximates T_{min} if *h* is larger than about 3H, where *H* is the characteristic height of the temperature profile, characterizing the height where $T–T_{min}$ decreases to $(T_{max}–T_{min})/e$. Thus, the index of refraction $n(T)$ of air is practically constant outside the hot air layer with a thickness of 3H shaded by grey in Fig. 1. The gradually bending ray-path returns at the turning point *P* and propagates toward the eye of the pelican, the horizontal distance of which from P is x_P. The ray-path is practically straight in

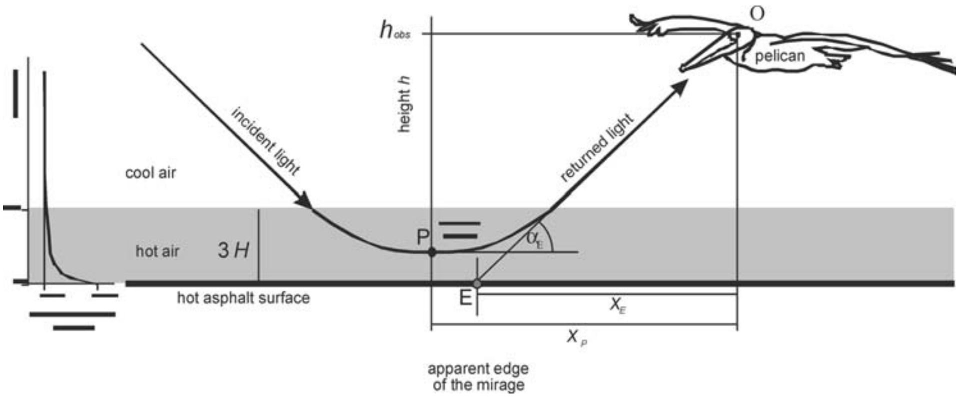

Fig. 1. Schematic tracing of the ray of light taking part in the formation of the apparent edge *E* of a mirage above a horizontal hot asphalt surface viewed by a brown pelican gliding with eyes at height h_{obs}. The exponential decrease of the air temperature $T(h,H)$ from T_{max} to T_{min} with increasing height *h* is shown in the left inset, where *H* is the characteristic height of the temperature profile above the asphalt surface

Table 1. Horizontal distance x_P (m) of the turning point P of the ray of light taking part in the formation of the apparent edge of a mirage above a horizontal, hot asphalt surface viewed by a gliding pelican with eyes at height h_{obs} = 0.5 m (Fig. 1) versus the maximal air temperature T_{max} computed for different values of the characteristic height H of the air temperature profile T(h,H) above the asphalt surface

		Maximal air temperature T_{max}			
		40 °C	50 °C	60 °C	70 °C
H	1 mm	122.19	87.77	72.77	63.97
	2 mm	122.52	88.02	72.98	64.15
	4 mm	123.19	88.51	73.40	64.53
	6 mm	123.86	89.01	73.82	64.91
	8 mm	124.54	89.51	76.24	65.29
	10 mm	125.22	90.00	74.66	65.67

the cool air and bends only in the hot air layer (grey in Fig. 1). The angle of the straight part of the returned ray taking part in the formation of the edge *E* of the mirage is α_E relative to the horizontal. The intersection *E* of the line of returned ray entering the eye of the pelican with the asphalt surface defines the apparent edge *E* of the mirage, the horizontal distance of which from the bird's eye is $x_E = h_{obs} / \tan\alpha_E$ (Fig. 1).

Figure 2 displays the paths of the returned ray of light of a mirage from the turning point *P* computed for T_{max} = 40, 50, 60 and 70 °C. These paths give the relationship between the height *h* of a pelican and the horizontal distance x_P of *P* from the bird's eye (Fig. 1). Table 1 shows the values of x_P for a pelican with eyes at height h_{obs} = 0.5 m versus T_{max} and the characteristic height *H* of the air temperature profile T(h,H) above the asphalt surface. We can see that x_P depends strongly on T_{max}, but its dependence on H is weak for 1 mm ≤ H ≤ 10 mm. Decreasing T_{max} from 70 to 40 °C results in that the value of x_P is approximately doubled.

Table 2 contains the values of angle α_E of the straight part of the returned ray of light taking part in the formation of the edge of the mirage viewed by a flying pelican with eyes at height h_{obs} = 0.5 m versus T_{max} computed for 1 mm ≤ H ≤ 10 mm. We can read from Fig. 2 and Table 2 that the straight part of the returned ray of light taking part in the formation of the edge of the mirage becomes more steep

Table 2. Angle α_E (measured from the horizontal) of the straight part of the returned ray of light taking part in the formation of the apparent edge E of the mirage above a horizontal, hot asphalt surface viewed by a gliding pelican with eyes at height h_{obs} = 0.5 m (Fig. 1) versus the maximal air temperature T_{max} calculated for 1 mm ≤ H ≤ 10 mm, where H is the characteristic height of the air temperature profile T(h,H) above the asphalt surface

T_{max}	40 °C	50 °C	60 °C	70 °C
α_E	0.24°	0.33°	0.39°	0.45°

Table 3. Horizontal distance x_E of the apparent edge E of the mirage above a horizontal, hot asphalt surface measured from a gliding pelican (Fig. 1) with eyes at height h_{obs} = 0.5 m (Fig. 1) versus the maximal air temperature T_{max} calculated for 1 mm ≤ H ≤ 10 mm, where H is the characteristic height of the air temperature profile T(h,H) above the asphalt

T_{max}	40 °C	50 °C	60 °C	70 °C
x_E	121.9 m	87.6 m	72.6 m	63.8 m

(α_E increases) as T_{max} increases. The consequence of this is that the horizontal distance x_E of the edge of the mirage from the pelican increases gradually from about 64 to 122 m if T_{max} decreases from 70 to 40 °C as Table 3 shows.

Above the sea surface brown pelicans generally use small local updrafts caused by the wind meeting the waves. Since these updrafts are small and temporary, pelicans fly close to the sea surface. Brown pelicans are among the bird species (e.g. vultures, large raptors, storks, albatrosses) with the highest known glide number (called also lift-to-drag ratio) *G*, since their wings have evolved to ensure gliding or soaring (http://www.earthlife.net/birds/flight.html). Thus, we can assume that brown pelicans can also glide efficiently above hot asphalt surfaces. Since the black vulture, *Aegyptius monachus* has the highest known glide number

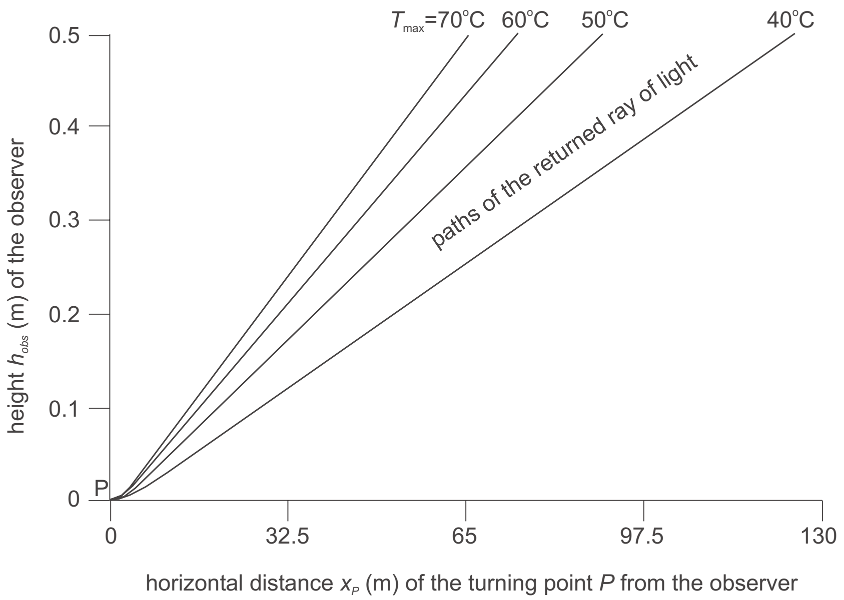

Fig. 2. Paths of the returned ray of light of the mirage from the turning point *P* computed for four different values of the maximal air temperature T_{max} above the horizontal hot asphalt surface. These paths give the relationship between the height h_{obs} of the eyes of a gliding pelican and the horizontal distance x_P of *P* from the bird (Fig. 1)

G = 22 (http://www.earthlife.net/birds/flight.html), the (unknown) *G*-value of brown pelicans is in all probability smaller than 22. This means that in still air a brown pelican loses more than 1 m in height for every 22 metres it travels horizontally during gliding.

On the basis of the dimensions (length ≈ 1.4 m, wingspan > 2.1 m) and the posture (Fig. 1) during gliding-flight (with neck folded) of brown pelicans (ROEVER 1974), the eyes of a gliding pelican cannot be nearer to an asphalt surface than about 0.5 m. This height enables only gliding without any flap of the long wings. Thus, $h_{min} \approx 0.5$ m is a reliable estimate of the critical minimum height, from which there is no return (i.e. the landing cannot be interrupted to take flight again) if an exhausted pelican began to land by gliding. Since for brown pelicans $G_{pelican} < G_{vulture} = 22$, the distance *d* necessary to land by gliding from height h_{min} is smaller than $G_{vulture} \times h_{min} = 22 \times 0.5$ m = 11 m. According to Table 3, for 1 mm ≤ H ≤ 10 mm the horizontal distance x_E of the edge of the mirage from a pelican gliding with eyes at height $h_{obs} = h_{min} = 0.5$ m is $x_E = h_{obs} / \tan\alpha_E \approx 122$, 88, 73 and 64 m, if the maximal air temperature T_{max} is 40, 50, 60 and 70 °C, respectively. Consequently, $x_E (h_{min}) >> d(h_{min})$, and thus the condition $x_E(h_{min}) \leq d(h_{min})$ is not satisfied. It is clear from Table 3, that for $T_{max} \leq 70$ °C and $h_{min} = 0.5$ m the condition $x_E(h_{min}) \leq d(h_{min}) = G_{pelican} \times h_{min}$ would be satisfied only if the glide number $G_{pelican}$ of brown pelicans were not smaller than $G^* = x_E/h_{min} = 63.8$ m / 0.5 = 127.6. However, $G_{pelican} < 22$ is very much smaller than G*.

From the above we conclude that the brown pelicans observed at the asphalt surfaces in the desert of Arizona would have had no chance to reach a water surface by gliding, which would have been so distant as the edge of the mirage. Since both $x_E (h_{obs}) = h_{obs} / \tan\alpha_E$ and $d(h_{obs}) = h_{obs} \times G_{pelican}$ are proportional to the height h_{obs} of the eyes of gliding pelicans, our conclusion is independent of h_{obs}, i.e. it is valid also for $h_{obs} > h_{min}$. Pelicans should know by experience the relation between height loss and travelled distance (i.e. the glide number) during their gliding-flight. Thus, the brown pelicans observed in Arizona should have known independently of their height above the asphalt road that they cannot reach the distant water-imitating mirage by gliding, and thus they will be forced to land on the asphalt.

DISCUSSION

In the opinion of the experts of WCAGFD (PITZL 2004), the brown pelicans observed in the Arizona desert were fooled by the mirage visible above asphalt surfaces. However, here we presented two optical counter-arguments of the hypothesis that a brown pelican can hope to land on the distant shimmering part of a hot asphalt road. The first counter-argument is trivial: The edge of a mirage can never be reached, because it continuously moves away when the observer tries to approach it. The second counter-argument originates from our computations: We showed that the edge of the mirage from a gliding brown pelican is so distant that the bird cannot reach it by gliding, even if the edge did not move off, independently of the beginning height of gliding.

In sunshine a dark asphalt surface in a desert has a higher temperature than the sandy ground. We showed that the consequence of a lower ground temperature (i.e. lower T_{max}) is that the edge of the mirage is visible more distant (Table 3). Hence, in sunshine the mirage is visible nearer above the (hotter) asphalt road than above the (cooler) sandy ground. This may be one of the reasons why the brown pelicans observed in the Arizona desert landed on the asphalt road rather than on the sandy ground. Note, however, that pelicans landing somewhere on the desert sand far from asphalt roads could practically not have been observed.

The landing of pelicans on an asphalt road could also be explained by the wetness of the asphalt, since the experts of WCAGFD have already observed pelicans that landed on wet asphalt roads in the Arizona desert (http://www.libertywildlife.com/pelican_bird.html). The reflection of light from a wet asphalt surface (Fig. 3) is different from the gradual refraction and total reflection of light from the warm air layer with a gradient index of refraction above a hot asphalt surface (Fig. 1). The horizontal distance x_R of the point *R* of reflection of light from a wet asphalt surface is $x_R = h_{obs} / \tan\alpha_R$ from a pelican gliding with eyes at height h_{obs}, where α_R is the angle of reflection relative to the horizontal (Fig. 3). When the asphalt is wet,

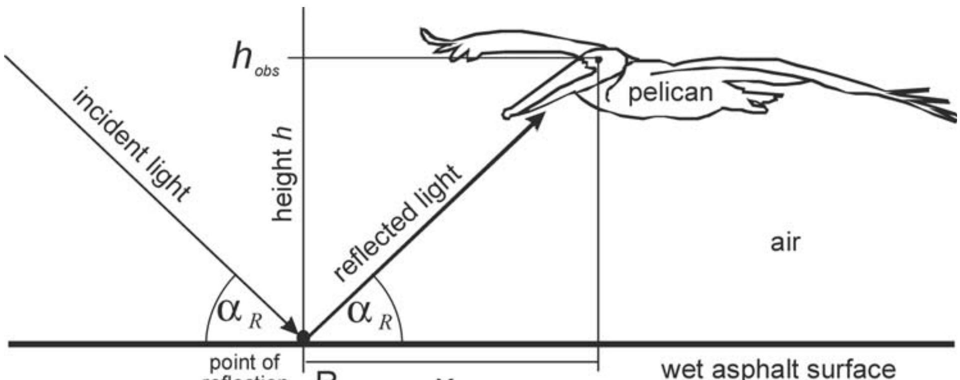

Fig. 3. Schematic tracing of a ray of light reflected from a horizontal, wet asphalt surface viewed by a brown pelican (*Pelecanus occidentalis*) gliding with eyes at height h_{obs}. Pelicans often glide effortlessly only about 50–60 cm off the water surface. Then their head is carried over the shoulders with the neck in a vertical S-curve

much amount of (sun and/or sky) light is reflected from it, if α_R is small enough. Thus, an asphalt surface can appear quite shiny for a flying pelican looking at grazing (small) angles α_R to it. If $h_{obs} = h_{min} = 0.5$ m and $\alpha_R = 4°$ (for which the reflectivity of asphalt surfaces is high), for example, $x_R = 7.15$ m, which is much smaller than the glide distance $d(h_{min}) = G_{vulture} \times h_{min} = 22 \times 0.5$ m = 11 m for the glide number $G_{vulture} = 22$ of black vultures. Hence, the horizontal distance x_R of the shiny part of a wet asphalt surface from a gliding pelican is much smaller than the distance x_E of the edge of the mirage (Table 3). Consequently, brown pelicans could hope that they can reach the shiny part of a wet asphalt road by gliding, even if their glide number is not so great as that of black vultures. If the dry asphalt surface is smooth enough, the same reflection phenomenon occurs, which could also deceive water-seeking flying pelicans.

On the other hand, the horizontal distance x_E of the edge *E* of a mirage is $x_E = h_{obs} / \tan\alpha_E$ from a pelican gliding with eyes at height h_{obs}, where α_E is the maximal angle of returned light relative to the horizontal taking part in the formation of *E* (Fig. 1). Tables 2 and 3 give the values of α_E and x_E, respectively for four different values of the maximal air temperature T_{max} immediately above the hot asphalt. Since α_E is much smaller (according to Table 2, it increases from 0.24° to 0.45° if T_{max} increases from 40 to 70 °C) then α_R, the value of $x_E = h_{obs} / \tan\alpha_E$ is much larger (Table 3) than that of $x_R = h_{obs} / \tan\alpha_R$. Therefore, brown pelicans could not hope that they can reach the distant edge of a mirage on a dry hot asphalt road by gliding. Their glide number should be higher than about 128 if they wanted to reach the edge of a mirage by gliding. A glide number of 128 (being about 6 times higher than the glide number $G_{vulture} = 22$ of black vultures possessing the highest known *G*-value among birds) certainly cannot be reached by brown pelicans even if they glided immediately above the asphalt surface with eyes at height $h_{min} = 0.5$ m.

In spite of the fact that the observed brown pelicans had no chance to reach the distant and continuously moving off mirage appearing on hot asphalt surfaces, they landed on asphalt roads in the Arizona desert. A reasonable explanation of this could be the extreme exhaustion of the birds. Another explanation could be that brown pelicans may not be "intelligent" enough to grasp that they can never reach the continuously moving off shiny distant part of an asphalt road.

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