RAINBOWS AND HALOES IN LIGHTHOUSE BEAMS

By C. FLOOR

PLON, Fysisch Laboratorium, Utrecht State University, The Netherlands

RAINBOWS are usually observed during showers when raindrops catch sunlight. Sometimes a rainbow is formed by refraction and reflection of light weaker than sunlight. Rainbows have been reported in moonlight (Minnaert 1954), the beams of ceilometers (Kangieser 1950; Jorgensen 1953) and searchlights (Harsch and Walker 1975). First we shall report and analyse our observations of rainbows in the beams of lighthouses and then go on to discuss the possible formation of haloes in these beams.

RAINBOW, BEAM OVERHEAD

The author observed rainbows during rain in the beams of lighthouses of the Dutch North Sea Islands of Terschelling (Floor 1978) and Schiermonnikoog. The parallel beams of these lighthouses rotate in a horizontal plane through the light-source. In Fig. 1, L is the light-source at height h above the observer O. The observer is standing directly under the beam with his back to the lighthouse. If the angle ψ between the horizontal plane and the direction of view is 42° a bright area is seen in the beam. If the lighthouse has an incandescent bulb (Terschelling) the edge of the bright area facing the light-source has a reddish colour. If $42° < \psi < 51°$ a dark area is seen in the beam. A second bright area is sometimes seen if $\psi = 51°$; in this case too a reddish edge faces the dark part of the beam. The second bright area is weaker than the first one. Even if the second bright area is absent or not detectable the beam is brighter if $\psi > 51°$ than it is if $42° < \psi < 51°$.

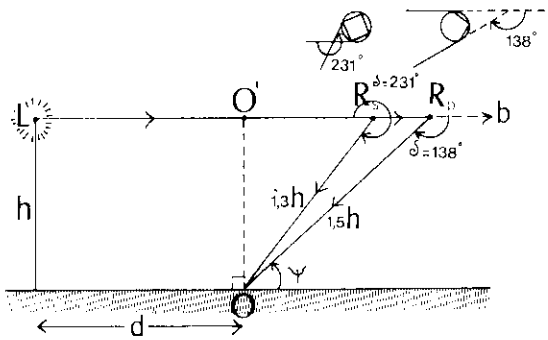

Fig. 1. Light-source L of the lighthouse is at height h above observer O. O is at distance d from the foot of the lighthouse. The beam b is horizontal and over the head of O. During rain O sees bright areas at R_p ($\psi = 42°$) (corresponding to a primary bow) and at R_s ($\psi = 51°$) (secondary bow). Between R_s and R_p ($42° < \psi < 51°$) the beam is rather dark

These bright and dark areas in the beam are formed in exactly the same way as a normal rainbow. If $\psi = 42°$ the bright area is a primary bow; if $\psi = 51°$ there is a secondary bow. The red edges of the bows are facing each other as in a normal rainbow. The dark area ($42° < \psi < 51°$) corresponds to Alexander's dark band, which is usually more easily visible in the lightbeam of a lighthouse than in sunlight. The values mentioned above apply to orange light. For light of other colours the values are slightly larger or smaller, due to the different refractive indices of water for the different colours of the spectrum.

When observed through a polarisation-filter the bright area appears to be polarised perpendicular to the plane of incidence (LRO, Fig. 1). This type of polarisation is the same as that of normal rainbows. Polarisation has also been noticed in rainbows in ceilometer-beams (Jorgensen 1953).

The most striking difference between a rainbow in the beam of a lighthouse and a normal rainbow is the wealth of colour in the latter and the absence of colour in the former.

The mercury vapour lights used in most of the lighthouses may be considered as 'nearly monochromatic' (Kangieser 1950), so that different colours cannot be observed. But even in the beam of a lighthouse that has an incandescent bulb, only a reddish edge was seen (Terschelling). The lack of some colours in the lighthouse beam may, in part, be due to the spectrum of the beam. The main reason that other colours are absent in that case is that the eye is less sensitive to colour at low light intensities. For the same reason in lunar rainbows most colours are lacking (Minnaert 1954).

Another difference is the distance to the rainbow as perceived by the observer. Although this distance is indefinite in the case of normal rainbows, the secondary bow, which is higher in the sky, is erroneously perceived to be at a higher altitude and further away from the primary bow. In the case of the lighthouse beam the situation is different. Here only the raindrops in the beam contribute to the formation of the rainbow. The primary bow is at a distance h/sin 42° = 1·5h from the observer, the secondary bow at h/sin 51° = 1·3h, so the secondary bow is nearer the observer.

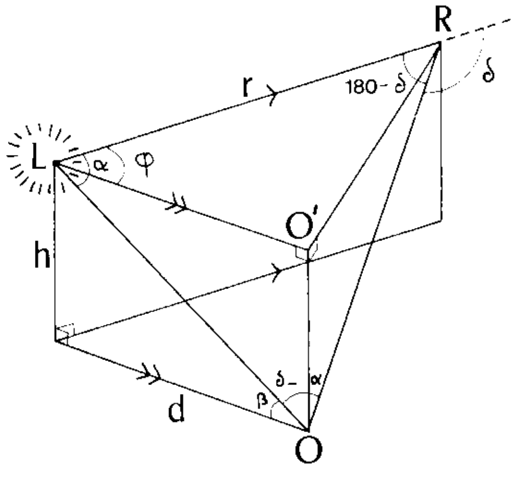

Fig. 2 Geometry of light rays forming rainbows in the rotating beam of a lighthouse. O sees a bright area in the beam. During rain the light from the light-source L is deviated by raindrops over an angle δ (δ = 138°, primary bow). O sees a bright area at R. r = LR. The orientation of the beam is given by φ (φ = δ: beam overhead). α = < OLR. For d and h see Fig. 1

RAINBOW, GENERAL CASE

When a lighthouse beam rotates, the bright area corresponding to the primary bow (δ = 138°) appears to move back and forwards along the beam. If the observer is looking at the beam through a polarisation-filter he has to change the position of the filter so that the bright area is at maximum light intensity. Fig. 2 gives the geometry of the situation. The movement of the bright area can be described by an expression for r/h as a function of the orientation φ of the beam (φ = 0: beam overhead).
Applying the sine-rule to triangle LRO (Fig. 2) one obtains:

$$\frac{r}{h} = \frac{(1 + [d^2/h^2])^{1/2}}{\sin(180°-\delta)} \sin(\delta - \alpha) \qquad (1)$$

The angle α is related to φ and d/h by:

$$\cos\alpha = \frac{[d/h]\cos\varphi}{(1 + [d^2/h^2])} \qquad (\alpha \leqslant \delta) \qquad (2)$$

This relation is derived by applying the cosine-rule to triangles LOR and LO'R and then by applying Pythagoras's theorem to triangle OO'R. Thus by solving Equation (2) for α and substituting α in Equation (1) we have an expression for r/h in terms of the ratio d/h, the orientation of the beam φ and deviation of the beam δ, namely

$$r/h = [d/h]\cos\varphi - (1 + [d^2/h^2]\sin^2\varphi)^{\frac{1}{2}}\cos\varphi \qquad (3)$$

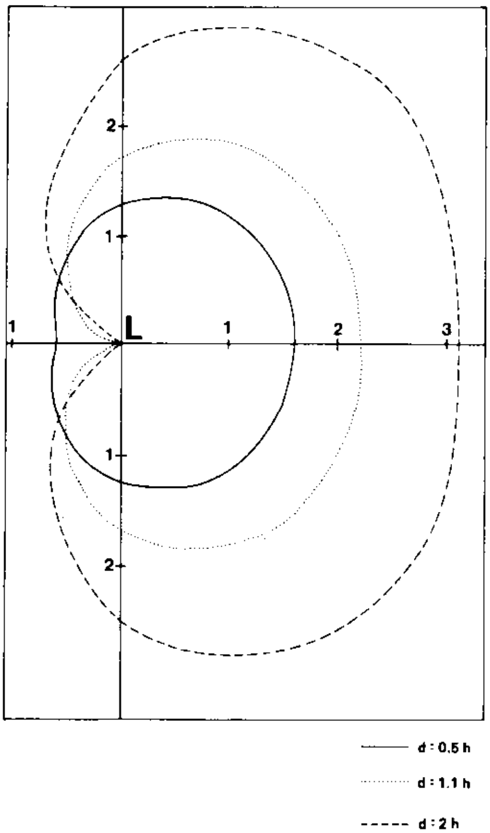

Fig. 3. Horizontal plane through L. The curves indicate the points in the plane where the observer sees the primary bow. The observer is directly below the horizontal axis of the figure at distances 0·5h, 1·1h, and 2·0h from L respectively. (For h see Fig. 1.) The solid curve is for d = 0·5h, the dotted curve for d = 1·1h and the dashed curve for d = 2h

Fig. 3 shows plots of r/h for the primary bow ($\delta = 138°$) for d = 0·5h, 1·1h and 2·0h. The figure can be interpreted as follows: the plane of the drawing is the horizontal plane through the light-source L in which the beam rotates. The axes are marked in units of h. The curves give the points R where the observer sees the primary bow and indicate the positions of the raindrops that contribute to the formation of the bow. For example, when d = 2·0h the observer is located beneath 2 on the horizontal axis of the figure and observes the primary bow at points on the dashed curve as the beam rotates.

As is readily derived from Equation (3), if d/h = 0 the curve is a circle with centre L and radius r = – h cot 138° = 0·9h (not shown). If d/h = 1·1 then for φ = 180° r = 0, and the curve passes through the light-source L. The primary bow then begins and ends its movement along the beam at L.

The results shown in Fig. 3 are consistent with observations made by the author near the above-mentioned lighthouses. In the case when d = 2·0h the rapid approach and retreat of the bow as the beam passed overhead (φ = 0) was very significant.

The author made interesting observations near the lighthouse of Vlieland (another Dutch North Sea Island). This lighthouse has divergent beams, which illuminate a quarter of the horizontal plane through the light-source on either side of the lighthouse. Thus the rainbow observed was not just a small bright area but was part of a bright curve, like the curves shown in Fig. 3.

Inspection of Fig. 2 also shows that the position of the plane of incidence LRO alters with the variation of φ. This explains the variation observed in the plane of polarisation during the rotation of the beam.

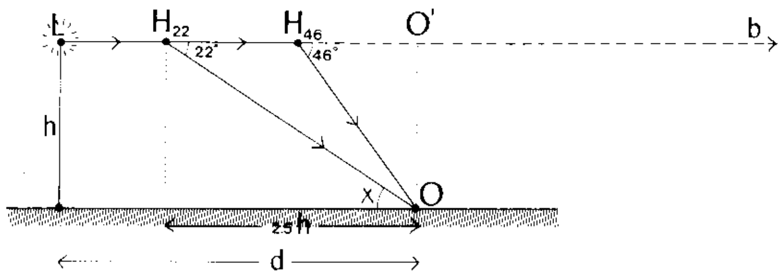

Fig. 4. During snow or in floating ice-crystals at temperatures far below freezing, O is likely to see bright areas at H_{22} (χ = 22°) (22°-halo) and H_{46} (χ = 46°) (46°-halo). (For b, d and h, see Fig. 1)

HALOES

Just as rainbows originate from a 138° deviation of sunlight caused by raindrops, the common 22° halo originates from a 22° deviation of sunlight caused by ice-crystals (yellow-light). The exact value of this deviation depends on the colour of the light, just as in the case of the rainbow. Haloes have also been observed in moonlight and in light from street-lamps (Minnaert 1954). In addition, haloes have been seen at or near the surface of the earth in freshly-fallen snow and in floating ice-crystals (Minnaert 1954) at temperatures far below freezing. It is probable that in these weather conditions haloes may also be visible in the beams of ceilometers, searchlights and lighthouses. As the deviation in the case of the common halo is 22°, ground-based observations near searchlights or ceilometers are usually impossible. The horizontal beam of a lighthouse however does make observations possible if the distance d > h/tan 22° = 2·5h (Fig. 4).

Just as when observing solar haloes, one has to make sure that the light source is behind the roof of a house, a tree or some other object. If the angle between the horizontal plane and the direction of view is 22° (observer facing the lighthouse, beam overhead) a bright area should be visible, possibly with a reddish edge towards the lighthouse (Fig. 4). Nearer the lighthouse the beam is likely to be darker since the sky looks darker inside the

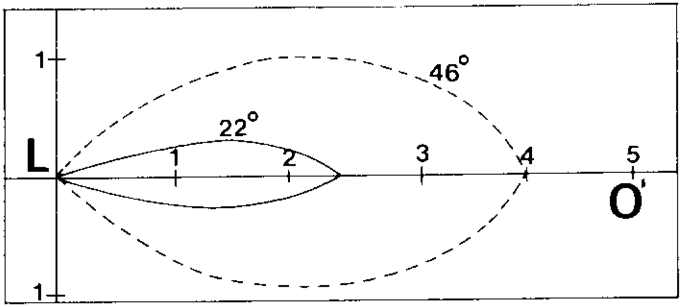

Fig. 5 Horizontal plane through L. The curves indicate the points in the plane where O is likely to see the 22° halo. O is directly below O′ facing the lighthouse at distance 5h (for h see Fig. 1)

22° halo. Hattinga Verschure (1979) has observed this kind of phenomenon in floating ice needles in the beam of a torch.

Yet another bright spot may be visible if $\delta = 46°$, corresponding to the 46° halo. By means of the equations (1) and (2) and taking $\delta = 22°$ (22° halo) or $\delta = 46°$ (46° halo), the movement of the haloes along the beam can be computed.

Fig. 5 gives an example for d = 5h: the haloes are visible for only a short time during each rotation.

ACKNOWLEDGMENT

The advice of Miss S. M. McNab in the preparation of this manuscript is gratefully acknowledged.

REFERENCES

Floor, C. (1978) Regenboog in de lichtbundel van een vuurtoren. *Zenit*, **5**, pp. 274–277

Harsch, J. and Walker, J. D. (1975) Double rainbow and dark band in searchlight beams. *Am. J. Phys.*, **43**, pp. 453–455

Hattinga Verschure, P. P. (1979) Waarnemingen van optische verschijnselen in februari 1979. *Weerspiegel*, **6**, pp. 147–148

Jorgensen, N. L. (1953) Polarisation of light from illuminated areas in a ceilometer beam during rain. *J. Meteor.*, **10**, pp. 160–164

Kangieser, P. C. (1950) Refraction phenomena affecting ceilometer observations. *Mon. Weath. Rev.*, **78**, pp. 211–216

Minnaert, M. (1954) *The nature of light and colour in the open air*. Dover Publ. New York