NOTES ON SOME ABNORMAL REFRACTION PHENOMENA IN THE ATMOSPHERE

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To geodesists and astronomers atmospheric refraction is a phenomenon, which makes it necessary to introduce corrections to the observations of carefully performed measuring series. Such corrections are generally obtained from tables giving values, which are applicable under "normal" or standard conditions. These conditions may be taken as more or less obtaining with a mean variation of temperature with height in the atmosphere - in the troposphere mainly a decrease of 0,6 - 0,7°C per 100 m.

However, in the low layer of the atmosphere there often occur situations, which deviate markedly from such standard conditions. In some specific weather situations and in some geographical regions the deviations may become especially marked. The influence of atmospheric refraction upon astronomic and geodetic measurements may then become exceptional and, besides, almost attain a random character.

In the winter, with strong cooling of the earth's surface, so-called surface inversions are common. Temperature then increases with height in the low layer, from the surface and some distance upwards. Such situations are common in fine-weather situations, especially when the ground is snow-covered. They are thus common at high latitudes in the winter. They are also found in late spring and early summer over the sea, i.e. at a time when the air is heated over the land, but the sea is still cold.

In summer - or in the warm zone - the heating of the ground in daytime gives rise to an abnormally strong temperature decrease with height in the layers close to the surface. Such conditions will not be considered here.

The meteorologist is mainly concerned with the atmospheric refraction phenomena as such and their varying appearance under different meteorological conditions, especially in extreme situations. To geodesists and astronomers the abnormal refraction phenomena are, however, a mere nuisance. Due to the stochastic character of the ensuing "errors" these cannot be eliminated properly by introducing corrections.

E. Tengström and G. Teleki (eds.), Refractional Influences in Astrometry and Geodesy, 343–350.

Let us have a closer look into the matter.

The refraction index n of air is a function of air density ρ and can be written

$$n = 1 + k \cdot \frac{\rho}{\rho_o} \qquad (1)$$

where $k = 2{,}93 \cdot 10^{-4}$ for "white" light,

ρ_o = the density of air at NTP (= 1013,2 mbar and 0°C).

With a temperature inversion - i.e. with a temperature increase with height - density ρ thus decreases more rapidly with height than in the normal case.

With refraction phenomena located to the surface layers, e.g. in connection with a marked surface inversion some 5-10 m thick, pressure p may be considered as constant within the layer. Density ρ and refraction index n are then for all practical purposes determined by temperature alone. The surfaces of equal refractive index n therefore run parallell with the isothermal surfaces.

Analogous conditions are found within inversions situated at higher levels in the atmosphere. In some cases, however, the inversions are so thick, especially in the polar regions, that the vertical variation of pressure p must also be considered.

The paths - or rays - of light can be derived from Snell's equation, viz.

$$n \sin \alpha = \text{const } (= n_o \sin \alpha_o) \qquad (2)$$

or in the modified form valied for spherical equidensity surfaces

$$rn \sin \alpha = \text{const } (= r_o n_o \sin \alpha_o) \qquad (3)$$

The index "0" marks values at a certain point of reference along the ray, often at the surface. The denotations are given in Fig. 1. Generally the surfaces of equal density are supposed to be strictly horizontal.

By using the first equation the equidensity surfaces are thus supposed to be horizontal planes; by using the second equation they are supposed to be spherical, r being the distance from the considered point of the ray to the earth's centre.

Knowing the vertical variation of density it is thus possible to compute in detail the rays of light, which originate from a certain object, or those rays which reach our eye. We have here only to measure the vertical variation of the temperature with height and if necessary, besides, pay attention to the vertical decrease of pressure, compare above.

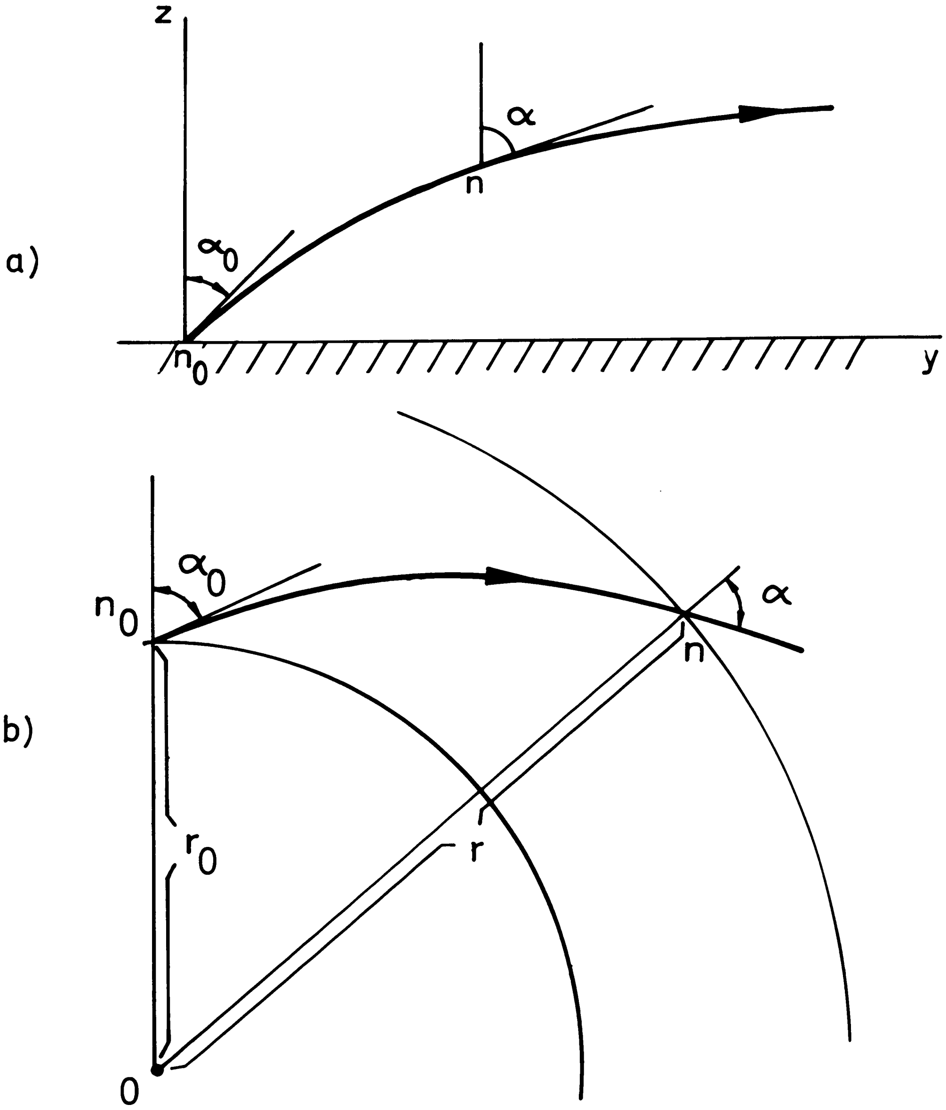

Fig. 1 Atmospheric refraction:
a) the surfaces of equal refractive index n are supposed to be horizontal planes;
b) the same surfaces are supposed to be spherical.

With marked refraction phenomena in the lowest layer - say up to 10 m - we can generally use the first equation; with refraction phenomena within thicker layers we must use the second equation, i.e. pay attention to the curvature of the equidensity layers.

The vertical variation of n is obtained from measurements of the temperature at different heights. In the lowest layer temperature is obtained from thermometers (preferably electric thermometers) mounted at a number of heights along an observation mast. If the temperature variation with height is wanted in more detail we can besides use a ventilated thermometer, which can be moved upwards and downwards along the mast. For thicker layers - say up to 500 m - it is possible to obtain detailed information from a tethered balloon equipped with suitable instruments. Such a balloon can analogously be moved upwards and downwards. If still thicker layers must be considered, data can be obtained from radiosonde ascents.

It is thus possible to obtain the refractive index and its vertical variation quite easily at the place of observation and at the time of recording.

A temperature inversion is, however, not a phenomena which remains more or less unchanged with time and in the horizontal. Internal waves are generated in the highly stratified air. Also more sudden and unexpected changes do occur. An inversion is also affected by the topography of the underlying ground. This means that the equidensity surfaces may not be horizontal, nor may they remain unchanged with time or in the horizontal.

This means that the atmospheric refraction and the optical phenomena coupled to it often change with time in a highly unexpected manner. Refraction and optical phenomena may also be different in different directions. In such cases atmospheric refraction corrections cannot be obtained from mere tables.

In some situations the atmosphere offers more than one path to light to travel from object to eye - each one giving rise to a separate image of the object. The images are then observed in the vertical, one above the other. In some cases all rays from the object, within a certain angle, can pass into the eye of an observer. The atmosphere then behaves in principle like a cylindrical lens. The image of a dark object situated at a critical distance is seen like a vertical dark pillar. The "points" constituting the ground - or snow surface - are then drawn out vertically to present an image of the surface similar to a gigantic wall surrounding the observer at a distance of 1/2-5 km or more depending upon the value of the vertical gradient of the temperature, or rather, of the refractive index. Objects at greater distance may disappear from view. Upper inversions may in analogous situations make distant mountains appear like gigantic pillars.

A person walking away from the observer may in such situations suddenly appear double and - as suddenly - transform into a dark pillar and then disappear from view. The rays of light, which originate from him, cannot then reach the observer as they are bent downwards towards the surface before then.

One way to study the special type of mirage, which is characterized by total reflection is to derive the so-called vertex curve, i.e. the locus of points situated on the top (vertex) of the different rays, which "leave" the object and then become total-reflected on the way, Fig. 2. Knowing the refractive index and its vertical variation, the vertex curve is easily obtained.

With object and eye situated at the same height and supposing that the equidensity layers are horizontal and plane, the angle α_o (see Fig. 1) at the surface is obtained from the vertex curve and from Snell's formula, viz.

$$n_o \sin \alpha_o = n_v \sin \alpha_v \qquad (4)$$

Values at the vertex of the ray are here denoted with an index "v".

As $\alpha_v = 90^o$ we have

$$\sin \alpha_o = \frac{n_v}{n_o} \qquad (4')$$

In the more realistic case with spherical density layers we have to start from Eq. (3). This equation can, however, easily be transformed into one similar to Eq. (2), viz. by writing

$$r = r_o + z \quad \text{and} \quad N = n \left(1 + \frac{z}{r_o}\right),$$

z being the height above the ground (with $r = r_o$).

When the conditions are ideal, i.e. with strictly horizontal density layers, it is possible to study atmospheric refraction in detail. However, the conditions are seldom ideal. In the highly stratified atmospheric layers waves or even more irregular displacements occur, which give rise to changes in the angle of incidence of the light-rays and also to local increases and decreases of the vertical gradient of the refractive index n, compare above. A certain ray will then undergo fairly rapid changes in direction with time, and the general appearance of the mirages may also change markedly with time. Besides, the conditions in that respect may be different in different directions depending upon the character of the underlying surface. The undulations of the surface is here an important decisive factor. The appearance of the mirages and the magnitude of the refraction is then more or less unpredictable in its details.

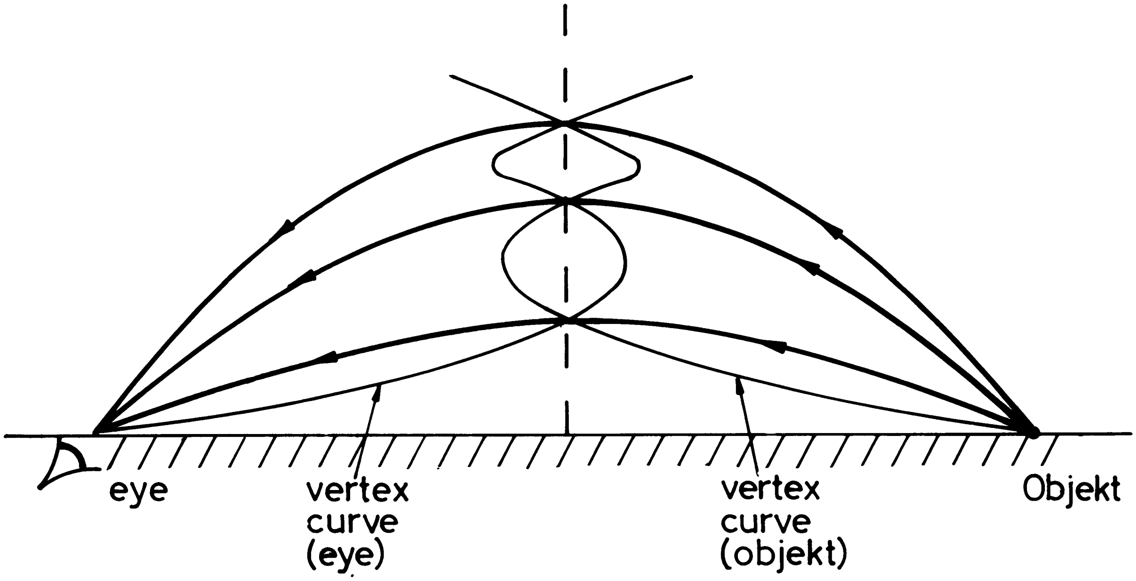

Fig. 2 From the variation of the refractive index n with height it is possible to derive the vertex curve, i.e. the locus of vertex points of rays leaving an object or reaching the eye of an observer. With object and eye at the same height the two vertex curves are the same and the vertex is situated at their intersection, i.e. halfway between object and eye.

The atmospheric refraction may also show short-periodic fluctuations. There exist small wavelets within the stratified layers and also irregular, small-scaled turbulent fluctuations. As a consequence a ray will pass through small volumes of air possessing densities which vary repeatedly along its path. As a result the image of an object is seen to change its position in an irregular way. This wellknown phenomenon - scintillation - may in extreme cases blot out the contours of surrounding objects; the latter may in extreme cases appear as a mere blur, even at distances less than 500 m. The wavelets within the stratified layers also give rise to another typical phenomenon. The upper rim of objects near the horizon, e.g. hills or hillocks, show small-scaled waves which are seen to move in the direction of the wind. Terrestrial scintillation becomes most pronounced in situations, when there exists a marked thermocline at a height of a few meters.

An abnormally great density gradient in the low layer of the atmosphere leads to an apparent displacement upwards of surrounding objects. Waves or other disturbances within these layers will affect this displacement, as both the density gradient and the angle of incidence of light are then changed. Even horizontal displacements may then occur. As mentioned previously, to an observer these vertical and horizontal displacements may seem to be almost stochastic. It should, however, be pointed out that marked displacements are found only near the horizon.

When a heavenly body is seen at the horizon, it is in reality well below it, viz. about 35' or roughly 0,6°. However, observations do exist, where the sun has been seen when in reality it was about 4° below the horizon. This phenomenon was first described by the Dutch polar expedition under W. Barentz in 1597. From the winter quarters of the expedition in northernmost Novaya Zemlya the sun was observed 14 days before it was due to appear at the end of the polar night. This observation was considered as a "good story" until in 1915 a similar observation was made in the Weddell Sea pack-ice by the "Endurance" expedition under Sir Ernest Shackleton (Visser, 1956). Later - in 1950 and 1951 - the sun was observed at Maudheim (lat. 71°S) when in reality it was 3,7° and 4,3° respectively below the horizon (Liljequist, 1964). On another occasion the sun was seen when it was in fact 1,0° below the horizon.

From Fig. 3 is seen that such abnormal refraction phenomena can be met with, when over long distances there exists a fairly undisturbed inversion, in which the solar rays are total-reflected. Such undisturbed conditions can best develop over an ice-covered sea, situated in the direction (from the observer) towards the sun at about local noon during the polar night. Such conditions existed for all the observations cited above. Over an ice-covered sea a marked inversion can develop in the low layer and this inversion is not affected by any underlying topography - the surface is more or less flat.

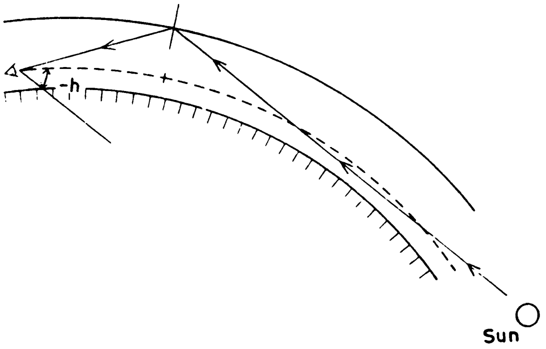

Fig. 3 The Novaya Zemlya phenomenon. Total reflection - one or more times - can make the sun appear above the horizon when in reality it should be one or more degrees below it. Note: the ray in the figure has for the sake of simplicity been drawn linear.

In conclusion we may note that temperature inversions at the surface or at height of a few hundred meters may introduce unexpected errors in geodetic measurements. Atmospheric refraction in situations with a marked inversion is generally such that reliable corrections cannot be introduced, at least not when the measurements are made close to the horizon. Inversions in the low layers are especially marked in the polar regions during the winter, but they are also found during fine-weather situations in the winter in the temperate regions. Marked inversions also develop in high and middle latitudes over the sea in spring and early summer, i.e. when the water is still cold, but the air over land is warm. In some situations this warm air may be driven out over the sea.

The geodesist is familiar with the adverse refraction effects met with over the land in the warm season, and generally he then avoids doing any measurements in the middle of the day. The atmospheric refraction, which occurs in the winter and also often in other seasons during the night due to cooling from below, is generally not considered in the same way. The atmospheric refraction - and the errors due to it - may on such occasions sometimes become even greater than in situations with a strong heating from below.

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