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Atmospheric Refraction Compensation in Terrestrial Photogrammetry

Simulations indicated that, over distances of several hundreds of metres, vertical refraction can be significant.

INTRODUCTION

NUMEROUS APPLICATIONS of precise analytical stereotriangulation in terrestrial photogrammetric surveys involving structural deformation measurements have been reported in the literature over the last decade or so (see, for example, Kenefick (1971), Brandenberger and Erez (1972), Erlandson *et al.* (1974), Veress and Sun (1978)). The recent adoption of long focal length cameras in displacement and deformation surveys has facilitated an increase in the useful range of photography from a few hundred metres, up to about 1 km. For example, a long term photogrammetric survey of the settling motions of a gabion wall, presently being conducted in Washington State, incorporates photographic distances of about 1000 m (Veress and Sun, 1978). In the present paper, the influence of atmospheric effects on the geometry of the imaging process is considered for cases where the photographic distance is greater than a few hundred metres.

An optical wave passing through the lower atmosphere from an object point to the frontal nodal point of a terrestrial camera describes a curved path as a result of the effects of vertical and lateral refraction. The magnitude of the subsequent image displacement resulting from the differences in the inclination angles of the arc of the wave path and the spatial chord at the camera, for a near horizontal line of sight, will principally depend on the focal length of the taking camera, the photographic distance, and the vertical distribution of the refraction field. Typically, atmospheric refraction

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ABSTRACT: The adoption of long focal length cameras in precise photogrammetric deformation surveys incorporating photographic distances of about 1 km has recently been reported. Over such ranges, optical wave path curvature due to atmospheric refraction can give rise to image displacements of up to 10μm when a 610 mm focal length camera is employed in normal meteorological conditions. A simulation is described which supports the contention that, over photographic distances of several hundred metres, the influence of vertical refraction on the imaging process can be significant and an adequate modeling of the resulting image coordinate errors will often be warranted.

Appropriate formulas relating the vertical refraction angle to image and apparent object space coordinate displacements are derived and different methods for the determination of vertical refraction are discussed. Particular emphasis is placed on the coefficient of refraction and the significance of the prevailing thermal stability conditions in the atmospheric boundary layer.

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gives rise to apparent object positional displacements of less than a millimetre over distances of around one hundred metres or so. However, the refraction effect increases in proportion to the square of the photographic distance and at a range of 1 km the apparent object point position can be in error by as much as 2-3 cm in normal meteorological conditions. In precise photogrammetric structural deformation surveys, the source of an error of this magnitude warrants consideration and hence there is a need for an adequate correction model for the effects of refraction.

In conventional aerial photography, atmospheric refraction causes a radial displacement of an image. This is not the situation in terrestrial photography where the camera axis is near-horizontal. In the latter case the most prominent image displacement is that due to vertical refraction, and this will typically result in a photo coordinate error Δy, assuming small kappa rotation. Thus, refraction models derived for aerial photography are not applicable in terrestrial photogrammetric surveys. In the present paper formulas are developed for the required image coordinate corrections, and a simulation study is carried out in order to assess the influence of particular solution techniques on the magnitude of the residual systematic errors due to vertical refraction. In addition, different methods of determining the refraction angle are summarized and the influence of meteorological factors is discussed.

VERTICAL AND LATERAL REFRACTION ANGLES

Fermat's principle states that when a light wave propagates through a refracting medium, its path of travel corresponds to that which results in the shortest travel time. For an optical wave passing through the lower atmosphere, the shortest travel time criterion is met by the light ray describing a curved path. The extent of curvature can be expressed in terms of the vertical and lateral refraction angles. This effect is illustrated in Figure 1.

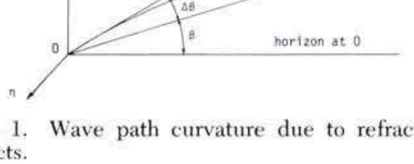

FIG. 1. Wave path curvature due to refraction effects.

Based on the solution of the eikonal equation for geometric optics by Moritz, the following expressions for the vertical and lateral refraction angles have been formulated by Brunner and Angus-Leppan (1976):

Vertical refraction angle $\Delta\beta$:

$$\Delta\beta = -\frac{10^{-6}}{S}\cos\beta \int_0^S \left(\frac{dN}{dh}\right)(S-\xi)d\xi \tag{1}$$

Lateral refraction angle $\Delta\alpha$:

$$\Delta\alpha = \frac{10^{-6}}{S} \int_0^S \left(\frac{dN}{d\eta}\right)(s-\xi)d\xi \tag{2}$$

where dN/dh and $dN/d\eta$ are the vertical and lateral gradients of refractivity;
β is the inclination angle of the chord;
S is the chord length; and
ξ is the integration variable along the chord.

Typically, applications of terrestrial photogrammetry involve chord lengths, S, ranging from a few metres up to several hundred metres. Over such distances, it can be safely assumed that the horizontal distribution within the refractivity field is uniform and, therefore, the gradient $(dN/d\eta)$ may be neglected as its value will approach zero. In the remainder of this paper, which stresses practical applications, small scale advection effects are not considered, and the treatment of the refraction correction deals only with the vertical refraction angle, $\Delta\beta$.

CORRECTION FOR VERTICAL REFRACTION

Figure 2 illustrates the geometry of a typical terrestrial photogrammetric survey with the light wave path, OP, being subject to a vertical refraction angle, $\Delta\beta$. The refraction gives rise to an error, ΔZ, in the Z coordinate of the object point. This error will be independent of any phi rotation, and, for a terrestrial camera which has been leveled (kappa $\simeq 0$), the error, ΔZ, will appear as an

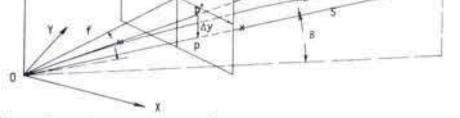

FIG. 2. Image coordinate correction, Δy, and object space coordinate correction, ΔZ, for vertical refraction.

image displacement, Δy, on the photograph. If the optical axis forms an angle, ω, to the XY plane, then the image correction at point p', Δy, can be derived as

$$\Delta y = -f \sec^2(\beta - \omega)\Delta\beta. \qquad (3)$$

Similarly, the correction to the Z coordinate of the object point is given by

$$\Delta Z = -D \sec^2\beta\Delta\beta \qquad (4)$$

where D is the horizontal distance between O and P.

In cases where the photo x coordinate axis is not aligned to the horizontal, the image displacement, Δ, due to vertical refraction can be resolved into Δx and Δy components. For moderately small kappa and omega rotations, these components can be determined with sufficient accuracy by the formula

$$\Delta x = -f \sec^2(\beta - \omega)\Delta\beta \sin\kappa \qquad (5)$$

$$\Delta y = -f \sec^2(\beta - \omega)\Delta\beta \cos\kappa \qquad (6)$$

DETERMINATION OF THE VERTICAL REFRACTION ANGLE, $\Delta\beta$

If similar meteorological conditions prevail along the wave path, then the vertical gradient of refractivity, dN/dh, can be assumed near-constant and Equation 1 can be simplified to the form

$$\Delta\beta = -\frac{S}{2}\cos\beta\left(\frac{dN}{dh}\right)\cdot 10^{-6} \qquad (7)$$

In certain meteorological conditions, when the wave path passes through regions of the atmospheric boundary layer which display markedly different vertical temperature distributions, the assumption of near-constant dN/dh is not always valid. However, it is possible to model the vertical distribution of refractivity with sufficient accuracy by empirical methods (Fraser, 1977) or by direct micrometeorological measurements of the components of the heat balance equation at the Earth's surface (Brunner, 1977). Such considerations indicate the significance of the determination of $\Delta\beta$ for the prevailing thermal stability conditions in the lower atmosphere at the time of photography.

In order to calculate the value of the angle $\Delta\beta$, the refractivity gradient, dN/dh, must first be determined. Refractivity, N, for optical wave propagation is given by the well-known formula of Barrell & Sears:

$$N = 79\,\frac{p}{T} - 11.25\,\frac{e}{T} \qquad (8)$$

where p is the atmospheric pressure in mb;
e is the partial pressure of water vapor, also in mb; and
T is the temperature in degrees Kelvin.

An expression for the vertical gradient of refractivity can be obtained by the differentiation of Equation 8 with respect to height, h. Neglecting terms in de/dh which are insignificant in the present context, and introducing a value for the pressure gradient, dp/dh, obtained from the hydrostatic equation, yields the following:

$$\frac{dN}{dh} = -\frac{79p}{T^2}\left(0.0342 + \frac{dT}{dh}\right) \qquad (9)$$

From this equation it is apparent that a knowledge of the prevailing vertical temperature profile is all that is required for the determination of the refraction angle, $\Delta\beta$. However, the accurate evaluation of dT/dh within some working height range can be associated with a number of practical difficulties and often it is appropriate to turn to tabulated values of dT/dh listed as a function of meteorological and surface conditions and obtained from very long-term empirical studies. Two such sets of tables have been given by Best *et al.* (1952) and Frankenberger (1955).

The determination of the refraction angle, $\Delta\beta$, directly in terms of dT/dh has not been employed in the test evaluations of the vertical refraction correction reported here. Rather, the angle, $\Delta\beta$, has been obtained via the coefficient of refraction, k, which will now be introduced. The two methods are essentially equivalent, although the latter has practical advantages in the geodetic context.

The coefficient of refraction, k, is defined as the ratio of the curvature of the wave path to the Earth's curvature. Again assuming constant dN/dh over the length of the ray path, k is given by

$$k = -R\cos\beta\left(\frac{dN}{dh}\right)\cdot 10^{-6} \qquad (10)$$

where R is the mean radius of the Earth. Combining Equations 7 and 10 yields an expression for $\Delta\beta$ in terms of k:

$$\Delta\beta = Sk/2R. \qquad (11)$$

This relationship (Equation 11) can also be obtained using geometrical considerations and a practical method of determining the refraction coefficient, k, is via trigonometric leveling. If the spheroidal heights of a camera station, O, and an object point, P, are known, then an estimate of the mean value of k can be obtained by calculating the individual coefficient, k_{OP}:

$$k \simeq k_{OP} = \frac{2R(S \sin \beta'_{OP} - \Delta H_{OP})}{(S \cos \beta'_{OP})^2} + 1 \quad (12)$$

where ΔH_{OP} is the spheroidal height difference between points O and P; and
β'_{OP} is the elevation angle determined by theodolite observations.

If the technique of reciprocal zenith distance observations is employed, then the mean value of the refraction coefficient over the chord, S, can be obtained without knowing ΔH_{OP} (Brunner, 1975).

In typical structural deformation surveys employing terrestrial photogrammetric techniques, the depth of spacing of the object points is small in comparison to the photographic distance. In such cases it is often convenient to work in plane coordinates and, thus, heights based on either a sea-level or ellipsoidal datum need to be corrected for curvature. Under the assumption just stated, the transformation can be achieved by a simple Z coordinate correction at each camera station, this correction being given by

$$\Delta Z_o = -(\bar{S} \cos \bar{\beta})^2/2R \quad (13)$$

where $\bar{S}$ is the distance between the camera station and the effective center of gravity of the object points; and
$\bar{\beta}$ is the elevation angle from the camera station to the same point.

With the ΔZ_o correction applied, Equation 12 can be rewritten in a form appropriate for use when the height datum is a plane:

$$k \simeq 2R(S \sin \beta'_{OP} - \Delta H_{OP})/(S \cos \beta'_{OP})^2 \quad (14)$$

If reciprocal vertical angles are observed between the camera station and an object point, then a mean value of k is given by

$$k = RS^{-1} \cos^{-2}\beta'_{OP} (\sin \beta'_{OP} + \sin \beta'_{PO}) \quad (15)$$

The value of k obtained from trigonometric leveling will not always be a sufficiently representative estimate for the layer of the atmosphere bounded by the working height range. Under certain meteorological conditions the vertical distribution of refractivity can display strong variability. As an example, a significant variation in the value of k with height may be found on a clear sunny day when the strongly superadiabatic conditions in the lowest few metres of the atmosphere produce a negative value for the refraction coefficient, yet at a height of a few tens of metres, well-mixed or near-adiabatic conditions can be expected, with the appropriate value of k being about 0.15.

Lack of the required equipment and/or facilities may preclude the direct determination of the refraction coefficient by either micrometeorological or geometric techniques. In such cases one can turn to published tables listing k as a function of height, in different meteorological conditions. Tables for the monthly mean diurnal variations of the refraction coefficient between the heights of 0.5 m and 500 m above the ground have been given by Brocks (1952). These tables were compiled by using meteorological data obtained over the plains of Central and Western Europe and particular reference has been made to conditions encountered on clear and dull days during mid-summer and winter.

In the simulation study reported here, three typical profiles of k have been considered, each profile being taken from the Brocks tables. It must be remembered that the empirically derived tabular mean value for k may not be particularly representative of the actual prevailing field values. However, one of the aims of this investigation was to examine the magnitude of the refraction coefficient in typically encountered meteorological conditions and, thus, mean values were deemed to be more suitable.

SIMULATION STUDY

In order to assess quantitatively the vertical refraction effects in a single stereo model of a terrestrial photogrammetric survey involving photographic distances of several hundred metres, a simulation study was conducted. To a large degree, the author's interest in a recent investigation of the settling motion of a gabion wall by photogrammetric techniques provided the motivation for this study. As a consequence the design parameters adopted in the simulation are similar to those found in the monitoring method for the gabion wall, the details of which have been reported by Veress and Sun (1978). Specifically, a camera focal length of 610 mm was adopted and the coordinate range of the chosen object point positions corresponded to a field of view of about 11½°. In addition, both camera axes were inclined to the horizontal, with an omega rotation of approximately five degrees.

Evaluation of the ΔZ errors was achieved through a comparison of results obtained from two solutions for the object point coordinates, one incorporating a refraction correction, the other not. For reasons which will become apparent, two methods of solution were employed.

First, the exterior orientation elements of each camera were assumed fixed, as were the object space coordinates of the camera stations. The coordinates of the object points were then obtained by intersection, simply using the standard collinearity equations. Common areas of application of a simple intersection solution technique would, for example, be long term deformation studies where camera station mounts are anchored in such a way as to allow the reestablishment of the exact same camera orientation at every exposure. The mounts are assumed to be free of deformation effects.

Second, a fully analytical solution was carried out in which all parameters were allowed to "float" according to assigned a priori variances. The simulated observations were obtained by employing a normal random deviate generator to perturb an otherwise perfect data set. The magnitudes of the perturbations were determined according to assigned standard errors of ±1 cm for the object control points and ±2 μm for the photo coordinate observations. No a priori constraints were imposed on the elements of exterior orientation, effectively giving each element zero weight in the final adjustment. This second method is generally applicable in photogrammetric surveys involving precise measurements in an environment where object control points can be situated in 'fixed' positions, in either a relative or absolute sense (see, for example, Kenefick, 1971).

The refraction coefficient has been shown to be a function of the vertical temperature profile in the lower atmosphere. However, it is common knowledge that this profile experiences a significant diurnal variation, the amplitude of which is dependent on the energy balance at the Earth's surface. In an effort to realistically reflect typically encountered field meteorological conditions in the simulation, three types of stratification of refraction have been considered. Brocks (1952) refers to these different stratifications as radiation type, isolation type, and transition type. The appropriate extracts from Brocks' tables showing the profiles of k selected for this study are given in Table 1.

The values in Table 1 reflect profiles typically found when the lower atmosphere is characterized by one of the three thermal stability regimes: unstable, neutral, or stable. Unstable conditions occur when the Earth's surface is strongly heated by incoming short-wave solar radiation (or insolation). Such atmospheric conditions are possibly the most commonly encountered during terrestrial photogrammetric surveys as they are normally found in the atmospheric boundary layer during clear daytime periods. As the unstable turbulent regime develops, increased turbulence dominated by free convection processes results in increased mixing. The increased mixing in turn leads to the formation of a more homogenous refractivity distribution with very little variability in the gradient, dN/dh, being encountered in the region from a few tens to hundreds of metres above the ground.

Neutral, or adiabatic conditions are normally found during the two daily transition periods. However, the neutral stratification is typically a short-term phenomenon rarely exceeding periods of more than a few tens of minutes. Adiabatic conditions may also prevail in the lower atmosphere when there is thick cloud cover accompanied by moderate winds. The principal reason for examining a profile of constant k rests in the fact that, as mentioned, near-neutral conditions are encountered in the upper region of the unstable regime.

Stable conditions are indicated by temperature inversions, for example, the typical night time inversion generated through ground cooling by outward long-wave radiation. Turbulent mixing is suppressed in stable conditions and, thus, strong refractivity gradients are developed. The values of

TABLE 1. VALUES OF THE REFRACTION COEFFICIENT, k, ADOPTED FOR THE SIMULATION STUDY.

Height above ground (m)	Unstable midday-summer	Neutral or adiabatic	Stable morning-winter
1.5	−1.7		0.8
4	−0.4	0.15	0.5
10	−0.05	0.15	0.35
40	0.12	0.15	0.25
100	0.14	0.15	0.21
300	0.15	0.15	0.20

k in the third column of Table 1 illustrate this behavior. Recent investigations (Brunner, 1977; Fraser and Brunner, 1977) have shown that temperature inversions offer the least favorable conditions for the adequate modeling of atmospheric refraction for geodetic applications. However, since stable conditions are commonly found on windless cloudy days, a stable stratification of refraction has been considered in the simulation study.

SIMULATION RESULTS

The coordinate errors, δZ, at each of nine selected object points, due to the effect of vertical refraction, are shown for the three stability conditions in Figures 3, 4, and 5. The most striking feature in the figures is the variation in the magnitude of the error, δZ, between the two methods of solution. To a large extent the variations encountered are to be expected, as for the case of object point coordination by simple intersection the magnitude of δZ is equal to the correction, ΔZ, given by Equation 4. In the fully analytical solution a priori constraints on the five object points (1,3,5,7, and 9) selected as control points (standard error = ±1 cm) bring about a considerable reduction in the Z displacements. This reduction is most pronounced in the case of stable conditions where the RMS error of δZ is reduced from 2.2 cm down to 0.2 cm. In addition, the systematic nature of the errors arising from the first solution method is not reflected in the coordinate displacements obtained using the analytical solution. In the latter case, the systematic error is either partially or fully absorbed by an upward shift of the computed Z coordinate of each camera station. This shift amounts to 9 cm for the stable, 1.2 cm for the neutral, and 4 cm for the unstable *k* profiles. Only in the neutral conditions instance, where the refraction error is constant, is the entire magnitude of the error absorbed by a Z coordinate shift at each camera station.

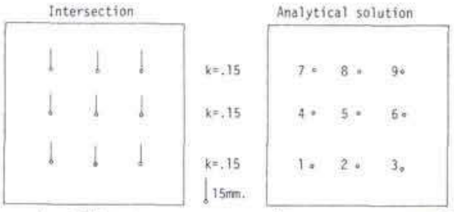

FIG. 4. Object space coordinate errors, δZ—adiabatic conditions.

The most probable estimates of the elements of exterior orientation, obtained from the analytical solution for the unstable and stable atmospheric conditions, differ slightly in value. However, whereas the differences in derived camera station coordinates amount to about 1 cm in *Y* and 5 cm in Z, the RMS errors in object point Z coordinates amount to only ±2 mm and ±4 mm respectively.

The principal influence of the vertical refraction effect is seen in apparent Z coordinate displacements of the object point position. However, deformation surveys typically involve the determination of the extent of lateral deflection in the structure as well as its settling. Results of the simulation study show the magnitude of errors in the determination of the *X* and *Y* coordinates, due to vertical refraction, to be in all cases less than 3 mm and in most cases of the order of 1 mm. These errors in lateral deflection determination arise mainly as a result of the introduction of a *y*-parallax component due to differential refraction. Typically, the distribution of the refraction field throughout the area of survey will be sufficiently near-uniform such that resulting errors in the calculated *X* and *Y* coordinates of an object point will be negligible. However, differential refraction can become significant if there is a large time lag between the exposure of successive photographs.

CONCLUSIONS

Although the atmospheric conditions

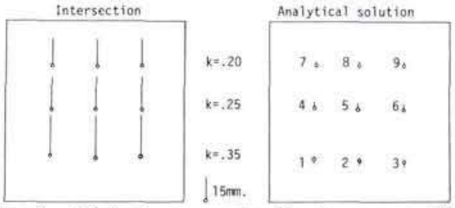

FIG. 3. Object space coordinate errors, δZ—stable conditions.

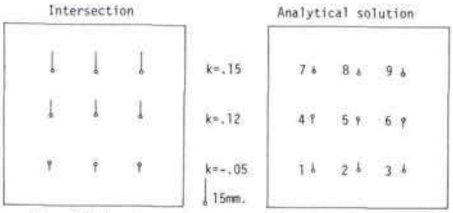

FIG. 5. Object space coordinate errors, δZ—unstable conditions.

represented by the vertical profiles of the refraction coefficient used in the simulation study will by no means adequately describe all field conditions, a few conclusions regarding the effect of vertical refraction in terrestrial photogrammetric surveys may be drawn.

From the results presented, it is apparent that the method of solution for the object point coordinates is of considerable importance. For the case where the elements of exterior orientation are assumed to be time invariant and object points are determined by intersection, the vertical refraction effect increases with the square of the photographic distance. Veress and Sun (1978) have reported achieving object point coordinate precisions ranging from a standard error of ±6 mm to ±20 mm, over a photographic distance of 1 km using a modified camera of 610 mm focal length. This study has shown that, in normal meteorological conditions, the vertical refraction effect can amount to 2 cm over this range. The magnitude of the error is thus significant when compared to the attainable precision. The required correction to photo coordinates, given by Equation 3, should be assessed in the context of the required accuracy specifications before the refraction effect is arbitrarily deemed insignificant and neglected.

The simulation study reported has shown that, when an analytical solution is employed with a priori constraint applied to the object control points, if the elements of exterior orientation are treated as completely unknown parameters, the errors in object point coordinates due to vertical refraction effects are reduced to a few millimetres over a photographic distance of 1 km. To a large extent the refraction effect will be absorbed by a shift in the Z coordinates of each camera station. However, if the elements of exterior orientation are treated as measured quantities and assigned a priori variances, then the vertical refraction effect must be considered in order to avoid the introduction of residual systematic errors into the analytical solution.

Terrestrial photogrammetric surveys often involve the monitoring of structural deformations over a long period of time. In such cases the problem of differential refraction between the periods of survey arises and it may prove advantageous to confine the photography to times of the day when the refraction distribution in the lower atmosphere is either similar to that encountered in the previous monitoring periods, or alternatively, is easily modeled by direct measurements or empirical means. With regard to the case of modeling the vertical profile of k, unstable (or clear day time) stratifications are most suitable as in these conditions an adiabatic profile ($k \approx 0.15$) in the atmospheric boundary layer can generally be assumed to be present above the lowest few tens of metres. In the surface layer, below the well-mixed region, k can be determined with sufficient accuracy by empirical means.

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