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Improved Model of Refracted Horizontal Angle: Dependency on Zenith Angle

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Abstract Refraction is always a major problem for the near-ground geodetic measurements. Thus far, there have been numerous studies showing the influences of atmosphere on the refracted ray leading to the variation in the distance and direction measurements. The refraction is projected into two non-correlated components on horizontal and vertical planes called horizontal and vertical refraction, respectively. Both impact the measurements in their corresponding directions. It is noted that, in terms of magnitude, the refracted zenith angle, in vertical plane, has always been assumed to be far larger than refracted horizontal angles (i.e., refracted horizontal angle is imagined to be minor or negligible). There are considerable productive understandings of vertical refraction influencing the vertical/zenith direction in the literatures. However, the limitation in determination of the horizontal (side or lateral) refraction is still a debatable issue. The research aimed to reveal the broader comprehension of the horizontally refracted ray affecting horizontal angle measurements. The presented model embraces the relationship between the zenith angle and refracted horizontal angle, which could be the desirable technique to computation of refracted horizontal angle at each zenith angle (i.e., ideally, it can be employed in the case of terrestrial laser scanning due to the change of zenith angle for every individual measured point). Thus, the dependency between vertical and horizontal refraction will be obvious.

Keywords: *dependency, horizontal refraction, influence of atmosphere, vertical refraction*

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1. Introduction

Minimising the uncertainty of geodetic measurements is demanding, particularly for the accurate horizontal angle measurements in tunnel surveying, for example. As a result, the important concern of horizontal refraction effects becomes a focus attention, and its correction should not be underestimated in highly accurate surveying.

According to the accepted literature, it has been proven when light beams cross through different medium they experience variable atmospheric conditions, therefore, being affected by environmental and atmosphere components. Thus, the electromagnetic wave (EM) may confront the following phenomena [1]:

a) extinction (i.e., the decrease in the density of light, and therefore also in its range),
b) diffraction (i.e., the deflection of the light beam in the immediate vicinity of barriers in the terrain),
c) change in the horizontal and vertical direction of the laser target – geodetic refraction [2],
d) change in the propagation of light beam and its related effects (electro-optical measurement of distance (EDM)) [3],
e) short-period, chaotic change of light beam location (e.g., blinking of the laser point).

None of the phenomenon above is the interest of this study apart from geodetic refraction. Geodetic refraction is the deflection of laser beam from its straight path as the result of the variation in:

i. air temperature,
ii. atmospheric pressure,
iii. humidity,
iv. and many other components of the atmosphere such as the carbon dioxide content of air, oil vapor of atmosphere.

The index of refractivity n and refractivity N (unitless values) are designated to mathematically estimate this deviation of a beam of EM through a line of sight (i.e., c is velocity of the wave into a vacuum $(299792458\, m/s)$, and v is propagation velocity of the identical wave into atmosphere (m/s)) [4]:

$$n = \frac{c}{v}, N = (n-1)\times 10^{6} \tag{1}$$

The refractive index n can then be resolved into $dn_x \equiv \eta$ and $dn_z \equiv \xi$ on horizontal plane and vertical plane (m^{-1}), respectively (Figure 1).

$$n = dn_y \vec{i} + dn_z \vec{k} \quad (2)$$

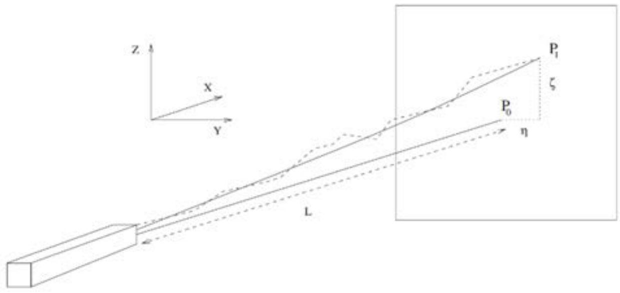

Figure 1. Horizontal and vertical refraction, *L and P0* are corrected distance and position of point, but due to refraction P_1 as the result of refracted range will be measured [5]

Here, $dn_y = \frac{dn}{dy}$ is horizontal gradient of refractive index, while $dn_z = \frac{dn}{dz}$ is vertical gradient of refractive index (m^{-1}).

In order not to be mistaken with z zenith angle, hereafter, the z will change to h regards as height $(m)\left(dn_z = \frac{dn}{dz} \equiv dn_h = \frac{dn}{dh}\right)$.

$$n = \frac{dn}{dy}\vec{i} + \frac{dn}{dh}\vec{k} \quad (3)$$

Comparing these two decompositions in terms of the value, the horizontal one is about one or two orders of magnitude less than vertical one. Therefore, the effect of refraction in angle measurements will be more considerable in vertical directions. Additionally, no direct correlation between the horizontal and vertical refraction of the curvature exists (i.e., no dependency between horizontal and zenith angles) ($\sigma_{dn_y,dn_h} = \sigma_{dn_h,dn_y} = 0$), according to [6,7].

2. Literature Review

3D point coordinates in laser-based instruments such as laser scanners and total stations are computed through the simple conversion from the Cartesian into spherical coordinate system (i.e., horizontal angle $0 \leq hr < 360°$, zenith angle $0° \leq z \leq 180°$ and range L):

$$\begin{bmatrix} L \\ hr \\ z \end{bmatrix} = \begin{bmatrix} \sqrt{x^2+y^2+z^2} \\ \tan^{-1}\left(\frac{y}{x}\right) \\ \tan^{-1}\left(\frac{\sqrt{x^2+y^2}}{z}\right) \end{bmatrix} \quad (4)$$

And reversely from spherical to Cartesian coordinates,

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L\sin z\cos hr \\ L\sin z\sin hr \\ L\cos z \end{bmatrix} \quad (5)$$

To obtain the corrected (non-refracted) values of $[x_c, y_c, z_c]$, it is necessary that the atmospheric influences on each polar element $[L, hr, z]$ will be eliminated. Since horizontal angle only varies the planar coordinates, Equations 6 and 7 will be given as follows:

$$\begin{aligned} x_c(dL, dhr, dz) &= x_m + dx \\ &= (L_m + dL)\cos(z_m + dz)\cos(hr_m + dhr) \\ &= L_c\cos(z_c)\cos(hr_c) \end{aligned} \quad (6)$$

$$\begin{aligned} y_c(dL, dhr, dz) &= y_m + dy \\ &= (L_m + dL)\cos(z_m + dz)\sin(hr_m + dhr) \\ &= L_c\cos(z_c)\sin(hr_c) \end{aligned} \quad (7)$$

Here, indices m and c stand for measured and corrected values, and dL, dhr and dz are resp. refracted range, horizontal and zenith angles changing both dx and dy which can be positive or negative (Figure 2).

Figure 2 indicates the schematic of refracted horizontal angle and horizontal angle measurements with exaggeration in the XY plane.

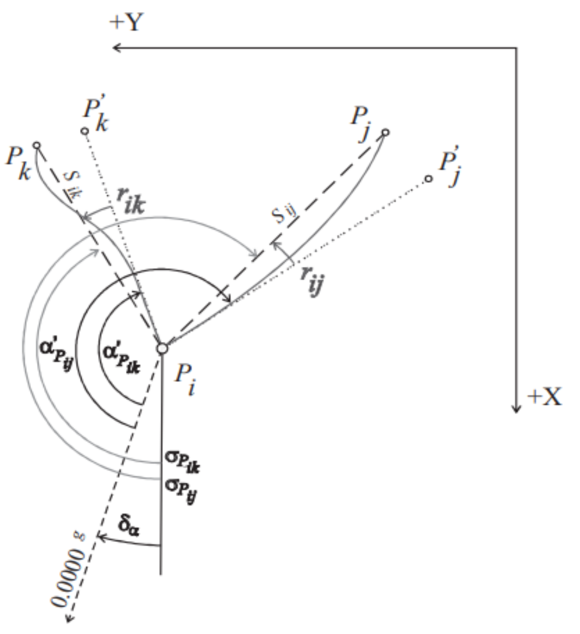

Figure 2. Effects of horizontal refraction in the plane X and Y, r_{ij} and r_{ik} are assumed to be the refracted horizontal angle [1]

The proper atmospheric model for range measurements has been already proposed by [3]. Additionally, the updated atmospheric model for refracted zenith angle was also proposed by [2]. The next concentration herein is to eliminate the refractivity dhr on horizontal angle measurement with consideration of horizontal refraction dn_y (Equation 3). Based on the arguments above, [6,7] acknowledged the refraction affects the planar coordinates separately due to the de-correlation between horizontal and vertical refraction.

3. Methodology

A refracted horizontal angle as the result of horizontal refraction (i.e., horizontal refraction in several textbooks is also called lateral or side refraction (or shift)) will occur in two different cases. When a beam ray travels from rarer to denser medium, the wave introduces the positive refracted angle leading to smaller measured horizontal than corrected one (Figure 3 above), whereas when the ray travels from denser to rarer medium, it introduces the negative refracted angle resulting in larger measured angle than corrected one (Figure 3 below)

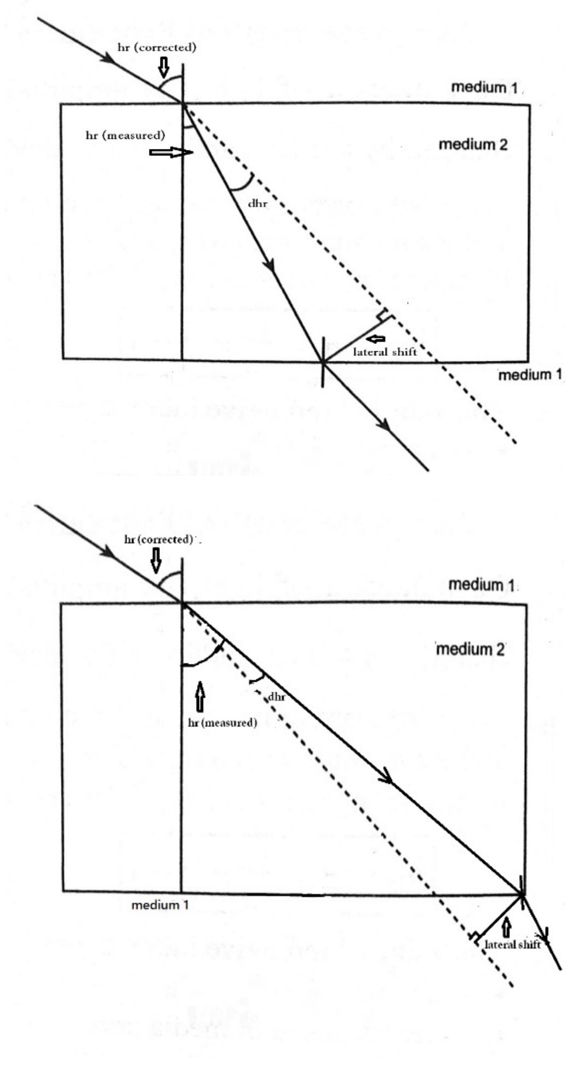

Figure 3. Refracted horizontal angle dhr and horizontal shift. Above: positive and below: negative refracted angle. The photos were modified by [1]

To understand the effect of refracted horizontal angles, [6] proposed the horizontal refraction of curvature dn_y, which can be described in the constant atmospheric pressure P $(mbar)$, a dependency with horizontal temperature gradient (HTG) $\frac{dT}{dy} = \frac{T_{i+1} - T_1}{y_{i+1} - y_1}$ where y is measured horizontally at right angles to the line (${}^0K/m$), and $T$is temperature ($°K$) as follows:

$$dn_y = -16.5 \frac{P}{T^2} \frac{dT}{dy} \tag{8}$$

In Equation 8, dn_y can be determined $(arcsecond\,/\,m)$ based on local horizontal temperature gradient. Reference [6] also mentioned the computation of refracted horizontal direction will hardly be practicable due to the existence of horizontal temperature gradient. The order or magnitude of possible lateral (horizontal) refraction can be anticipated as follows:

a) For a distance of about $3000\,m$, $1000\,m$ horizontally, $3000\,m$ vertically, and with $5°K$ hotter temperature, the average HTG difference will be $5°K$ per $1000\,m$ (i.e., $0.005\ {}^0K/m$). On the line of sight, HTG may experience lower amount, but the refracted angle reaches the maximum of $0.0015\,arcsecond/m$, and the total curvature in $3000\,m$ will be approximately 1".

b) Assuming a line of sight is two meters above the ground with the vertical temperature gradient of $0.3\ {}^0K/m$, HTG might be the same as $2\,m$ in the side of vertical rock in bright sunshine. A graze of $15\,m$ long through such a gradient would produce the curvature of 1".

c) Twist in a normally refracted ray is the other assumption of Bomford which is theoretically negligible [6]

Since the main restriction of Equation 8 is to determine the horizontal temperature gradient in the field, all former expectations were based on hypothesized models and no accurate value for HTG was presented, so far.

To thoroughly investigate the HTG, HTG is the distribution of temperature across the latitudes over the surface of the Earth. References [1,8,9] have carried out numerous laboratory observations to investigate to quantify this term. However, establishing the calibrated configuration for horizontal temperature gradient in a real scenario is not a straightforward task, because temperature changing across the Earth's surface (i.e., in the horizontal direction) is clearly contributed by several other metrological components. The responsible factors for the uneven horizontal distribution of temperature are [10]:

i) latitude,
ii) land and sea contrast,
iii) relief and altitude,
iv) ocean currents,
v) winds,
vi) vegetation cover,
vii) nature of the soil, and
viii) slope and aspect.

It is worth noting all above arguments influence HTG both at the surface and at different heights. Thus, it is evident that the horizontal distribution of temperature is uneven horizontally even though, so far, entire horizontal layers of atmosphere have been assumed to be horizontally stratified [6,7].

Reference [10] has developed the horizontal refraction (shift) dn_y in meter at each latitude with the assumption of flatness of the Earth from [11,12] which is a function of zenith angle z and wavelength λ (mm) [10].

1 https://simple.wikipedia.org/wiki/Refraction

$$dn_y = n(\lambda)\frac{\cos(z)}{\sin^2(z)}\frac{P(h)}{g.\rho s} \quad (9)$$

Where n is refractive index (dimensionless values), P atmospheric pressure $(mbar)$ at the certain of heigh $h\ (m)$, standard gravity g equal to $9.806\ m/s^2$, $\rho s = 1.225\ kg\ m^{-3}$ is the air density (defined at the standard condition of air [4], $t_{st} = 15°\text{C}$, and $P_{st} = 1007\ hPa$), and z is the zenith angle of non-refracted (corrected) beam ray.

Figure 3 graphically demonstrates the lateral shift $b = A'M$ which is the reference value that can be chosen either at ground level or at infinity, depending on the purpose of the calculation [10].

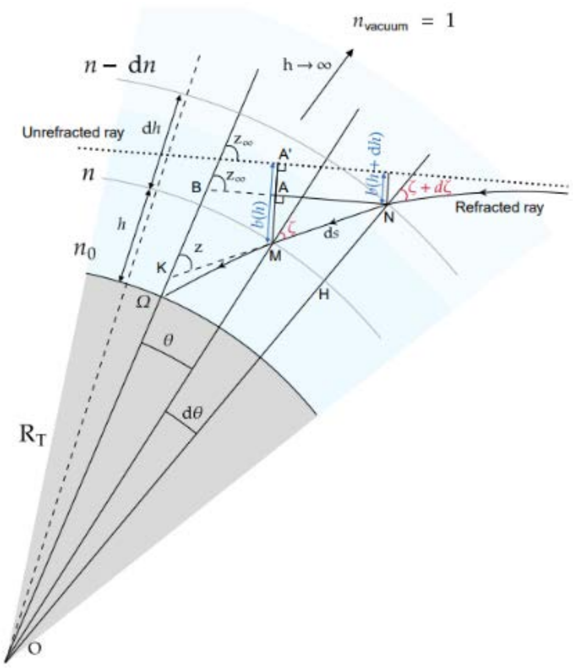

Figure 4. Lateral refraction b refracted Ω and non-refracted z zenith angle [10]

It is clearly seen the zenith angle (regardless of refracted or non-refracted) influences the refraction on horizontal angles. However, Equation 9 includes the non-refracted (corrected) zenith angle z_c, which composes of refracted zenith angle dz caused by vertical refraction and measured zenith angle z_m [2].

$$z_c = z_m + dz \quad (10)$$

Following arguments embrace the various terms available in Equation 9.

Refraction and refractive index: To address the refracted horizontal angle (Equation 9), [3] has modelled the refracted range based on numerous available refractive index models. One of the proposed models is adaptation of (International Association of Geodesy [IAG], 1999) [13] called Closed Formulae algorithm in 1999 to determine refraction in every favourable wavelength $\lambda\ (\mu m)$, temperature $T\ (^0K)$, pressure P and partial water vapor pressure $e\ (hPa)$ (i.e., please refer to [3] to follow up with several other represented models).

The phase or group dispersion equations are those equations have the capability to compute phase or group refractive index based on wavelength $\lambda\ (\mu m)$ within different modes of air (e.g., free of CO_2, water vapor of air (moist air), and carbon dioxide content of air). Respectively,

$$N(\lambda) = (n(\lambda) - 1)\times 10^6 = 287.6155 + \frac{4.8866}{3\lambda^2} + \frac{0.068}{5\lambda^4} \quad (11)$$

$$N(\lambda) = (n(\lambda) - 1)\times 10^6 = 287.6155 + \frac{4.8866}{\lambda^2} + \frac{0.068}{\lambda^4} \quad (12)$$

Atmospheric pressure: Assumed pressure in Equation 9 will be calculated at a certain height level above the Earth $h\ (m)$. According to Barometric formula, it is feasible to convert the pressure from a different height to the pressure at the ground heigh where most of terrestrial surveying measurements can take place. Based on the Barometric equation:

$$P(h) = Pe^{\left(-\frac{Mgh}{RT}\right)} \quad (13)$$

Where P is atmospheric pressure on the ground (hPa), M is molar mass of Earth's air $\frac{kg}{mol}$ which is equal to 0.02896, R is the universal gas constant $\left(= 8.3143\frac{Nm^0}{mol}K\right)$, and T is temperature $(°K)$.

Gravitational acceleration: Concerning the gravitational acceleration g, which is the other term in Equation 9, there is a relation between $g(h)$ gravitational acceleration at certain height (m/s^2) and the one at the near-ground layer:

$$g(h) = g\left(\frac{R}{R+h}\right)^2 \quad (14)$$

At the very close layer of ground layer $g(h) \approx g$ (i.e., there is no dramatic change between them).

By substitution three terms mentioned above and assuming $\lambda = 658\times 10^{-6}\ mm$ for refractive index, Equation 9 will be simplified by:

$$dn_y = 0.084\frac{\cos(z_c)}{\sin^2(z_c)}Pe^{\left(-\frac{0.0342h}{T}\right)} \quad (15)$$

Given the constraints of non-refracted zenith angle (Equations 10 and 15), the dependency between horizontal refraction and vertical refraction will become clear [2].

$$dz \propto dn_h \quad (16)$$

Where dz refracted zenith angle is computed in rad via L_c corrected distance of each target which is non-refracted range (m) and dn_h vertical refraction (m^{-1}).

$$dz = -\frac{L_c}{2}dn_h \quad (17)$$

Lastly, based on the small angle approximation via Taylor series expansion, refracted horizontal angle dhr in rad is given as follows (Figure 1):

$$\tan(dhr) \approx dhr = dn_y \cdot L_c \tag{18}$$

It is worth noting that not only is the effect of range dominating in both refracted angular measurements, but also its effects alongside zenith angle impact the refracted horizontal angle. It is inferred the observational correlation exists between three polar elements of 3D point coordinates (Equations 6 and 7).

In case the zenith angle is 90° (happens at horizon), the horizontal refraction (Equation 15) becomes zero. In other words, when observing in or near the horizontal plane, the horizontal refraction, logically, is minimised. However, it becomes maximum for the points close to zenith and nadir, although the model does not properly estimate the variable for those exactly at zenith $z = 0$ and nadir $z = 180°$.

4. Data Analysis and Discussion

Data analysis consists of the investigation of zenith angle measurements (refracted and non-refracted), and atmospheric analysis (pressure and temperature) on refracted horizontal angles. The atmospheric conditions of Newcastle, New South Wales, Australia [2] in February 2023 were assumed.

4.1. Zenith Angle Analysis

At the first attempt, the dependency of zenith angle, regardless of refracted and non-refracted one, on refracted horizontal angle is evaluated (Figure 5). Worth mentioning, the positivity and negativity of refraction in the following Figure were already illustrated in Figure 3.

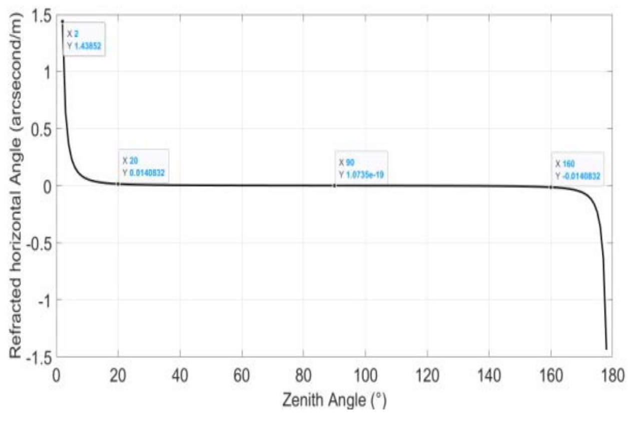

Figure 5. Refracted horizontal angle (*arcsecond/m*) w.r.t zenith angle (°). (i.e., zenith angle smaller and larger than 90° corresponds to above and below horizon, respectively)

The symmetric behaviour of Figure 5 depicts the refracted horizontal angle is considerably unchanged and insignificant for the points at the zenith angle between 20° and 160° (i.e., referring to above and below horizon, respectively), but the points closer to zenith and nadir experience the similarly significant refraction in an opposite direction (starting from $\pm 0.014\ arcsec/m$ to more than $\pm 1\ arcmin/m$). From above, two important points can be noted. Firstly, it will be a concern for terrestrial laser scanning observations, which are obtained with wider vertical field of view (FOV) particularly panoramic scanners. Secondly, the height of the observed target is one of the influencing factors for refracted horizontal angle.

It is also feasible to acknowledge there is quite negligible difference achieved from applying refracted or non-refracted zenith angle in Equation 15 due to the slight change in refracted zenith angle. In other words, despite the existing correlation between horizontal and vertical refraction, it can be overlooked.

4.2. Pressure and Temperature Analysis

Figure 6 and Figure 7 show the effect of atmosphere on refracted horizontal angle at different zenith angles (only above the horizon) and the comparison with older function proposed by Bomford in 1962.

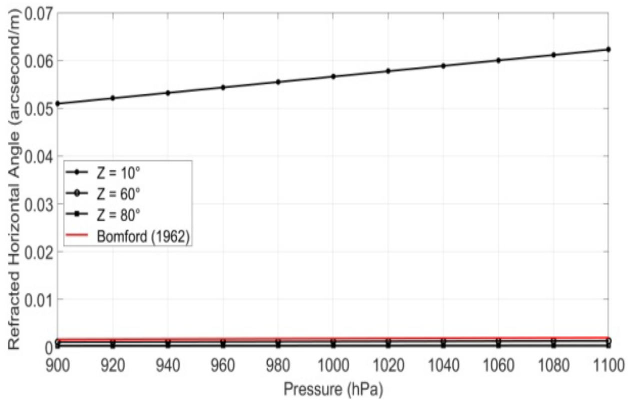

Figure 6. Refracted horizontal angle (*arcsec/m*) w.r.t pressure (*hPa*)

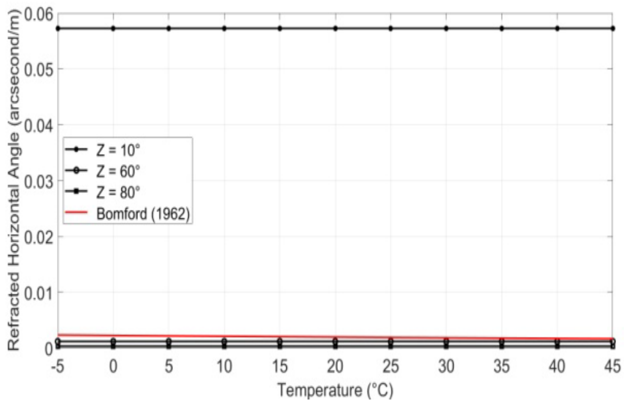

Figure 7. Refracted horizontal angle (*arcsec/m*) w.r.t temperature (°C)

As illustrated in Figure 5, the change of zenith angle approximately between 20° and 160° can be underestimated. However, refraction for horizontal angle will be particularly substantial for the points close to zenith and nadir which is here obvious at zenith angle of 10° close to zenith (correspondence to symmetric behaviour at z=170° close to nadir). Besides, Bomford's approximations [6] will be correct for the certain range of zenith angle, meaning that there are no correlations assumed between angular measurements which results in minor refracted horizontal angle in those ranges.

2 http://www.meteorology.com.au/local-climate-history/nsw/newcastle
http://www.bom.gov.au/akamai/https-redirect.html

In practice, the aim will be to eliminate the refracted horizontal angle over the longer range by consideration of atmospheric variations at certain zenith angle.

According to error of propagation, and constant zenith angle and range in Equations 15 and 18, $d(dhr)$ the variation of refracted horizontal angle caused by atmospheric changes in $arcsecond$ will be given by:

$$d\left(dhr\right)=\left[\frac{\partial\left(dhr\right)}{\partial P}dP+\frac{\partial\left(dhr\right)}{\partial T}dT\right]L\frac{\cos\left(z\right)}{\sin^{2}\left(z\right)} \quad (19)$$

Here, dT stands for temperature changes $(°K)$, and dP is pressure changes (hPa). Because dT is a difference in values, either $°K$ or ℃ can be taken. Therefore,

$$d\left(dhr\right)=\left[\begin{array}{c}0.084e^{\left(-\frac{0.0342h}{T}\right)}dP\\ +0.084Pe^{\left(-\frac{0.0342h}{T}\right)}\frac{0.0342h}{T^{2}}dT\end{array}\right]\cdot L\frac{\cos\left(z\right)}{\sin^{2}\left(z\right)} \quad (20)$$

Assuming the standard condition of atmosphere of Newcastle, and near-ground layer of atmosphere $h = 2\ m$ [2], Equation 20 will be expressed as follows:

$$d\left(dhr\right)_{[arcsec]}=\left[\begin{array}{c}\left(1.7\times10^{-6}{}_{[arcsec]}\right)dP_{[hPa]}\\ +\left(0.001\times10^{-6}{}_{[arcsec]}\right)dT_{[℃]}\end{array}\right]_{[arcsec]}\cdot L_{[m]}\frac{\cos\left(z\right)}{\sin^{2}\left(z\right)} \quad (21)$$

For instance, at the slope distance of $1000\ m$ and the change of 5 ℃ and $2\ hPa$ in temperature and pressure, respectively, the introduced refracted horizontal angle will be modelled such as Table 1:

Table 1. The effect of atmospheric changes on horizontal refracted angle w.r.t three assumptions of zenith angle

Horizontal Refracted Angle	Zenith Angle		
	Close to Zenith $0° < z \leq 20°$	Horizon $20° \leq z \leq 160°$	Close to Nadir $160° \leq z < 180°$
	$11'' \leq dhr \leq 0.03''$	$dhr \approx 0''$	$-0.03'' \leq dhr \leq -11''$

Given the atmospheric variations as an example, refraction at or near zenith or nadir over longer range will be further 10" on horizontal direction.

To sum up, considering of the range and vertical angle, alongside atmospheric variations, for accurate computation of refracted horizontal angle is necessary. Secondly, here the proposal is also modelled as the consequence of the atmospheric variations, height (zenith angle) and surface (range) rather than employing the Bomford's suggestion which roughly estimate the refracted angle with geometrically approximate value of HTG for a certain range of zenith directions. In other words, polar observations in Equations 6 and 7 are all correlated. Thirdly, we might disregard the refracted ones on horizontal refracted angle due to the small changes over range and zenith angle. Therefore, the insignificant correlation between vertical and horizontal refraction exists.

5. Conclusion

The current paper aimed to clarify the effect of atmospheric refraction of horizontal angle measurements. It has been shown the refracted horizontal angle is changed as the consequence of height (change in zenith angle) and obviously on the horizontal surface by range. It clearly demonstrates the zenith angle and corresponding range (regardless of their refractions) play an important role in refracted horizontal angle. It is understood in terms of terrestrial laser scanning, the applying of a wider vertical field of view (FOV) with panoramic scanners does lead to the larger systematic errors from refraction when viewing at or near zenith or nadir. On the other hand, the variations caused by atmospheric elements over larger distance have also been considered w.r.t temperature and pressure.

The future investigations could be to incorporate all non-refracted polar elements (particularly dominating range) to recalculate the 3D point coordinates as the result of consideration of their correlations to define the proper weighted least square to mitigate the effect of atmosphere on 3D point coordinates obtained from total stations or terrestrial laser scanner.

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Statement of Competing Interests

The authors have no competing interests.

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