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IMPROVEMENT THE MODELLING OF ATMOSPHERIC EFFECTS FOR ELECTRONIC DISTANCE MEASUREMENT (EDM): ANALYSIS OF AIR TEMPERATURE, ATMOSPHERIC PRESSURE AND RELATIVE HUMIDITY OF AIR

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Abstract. The atmosphere is an undeniable source of error for any geodetic instruments. Surveyors require to have an accurate approximation of distance measurements in order to accurately determine the 3D coordinate of points. Electronic Distance Measurements (EDMs) are employed to measure accurate range to the target. They are typically functioning by laser in the domain of light or near infrared of electromagnetic spectrum (EM). Snell's law has proved propagating wave through passing the different layers of atmosphere is deviated. This phenomenon is called the refractivity of wave. This deviation is introduced by different intersection between the beam and the object surface at different epochs of atmospheric change. By possessing the knowledge of group refractive index, it is possible to estimate the value of correction in ppm for measured distances caused by the variations in atmospheric elements. The changes in three components of air, temperature, pressure and humidity, in this study will be considered.

Keywords: atmosphere, deviation, EDM, electromagnetic spectrum, group refractive index, propagating wave, refractivity, Snell's law.

Introduction

The electro-optical distance measurement (EDM) is the well-known surveying instrument for measuring the distances. Three technologies so far recognized behind this optical length measuring system to estimate the distance between the instrument and target: time of flight (ToF), phase shift and wave form digitizer (WFD).

First, ToF technology calculates the distance based on the time of the light pulse from the instruments to the object and back to the instrument. It uses either pulsed modulation or continuous wave modulation. Figure 1 illustrates how the time of laser pulse is detected by the instrument.

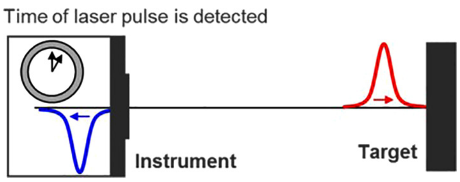

Figure 1. Time of flight technology (Maar & Zogg, 2014)

Second, phase shift method is based on the phase shift between the emitted and reflected signal and the number of full wavelengths. Phase shift conveys data by modulating phase of a signal. This method allows the evaluation into the total signal information, such as the entire signal shape and channel amplification, for more sensitive distance determination (Figure 2).

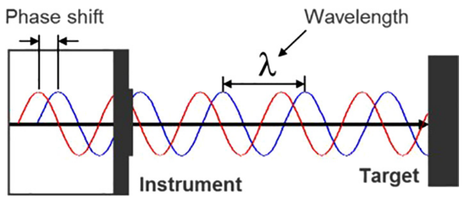

Figure 2. Phase shift technology

Third, WFD technology combines both available methods where the distance calculated based on the time between a start and stop pulse which is digitized out of the received signal (Figure 3).

To compare those technologies, ToF technology can be recommended for longer range EDM even though it brings

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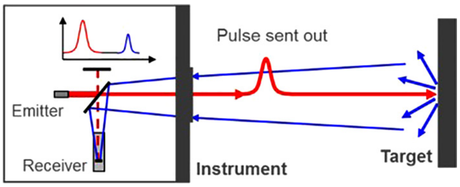

Figure 3. Wave form digitizer technique

larger laser spot and lower measurement accuracy than phase shift technology (Rueger, 1990).

The accuracy of electronic distance measurements highly depends on the accuracy of the wave propagating wavelength and its rate. The electromagnetic wave in the air is influenced by several atmospheric elements such as air temperature, atmospheric pressure of air, water vapor of air (humidity), the effects of carbon dioxide content, oil vapor of air, and the impacts of absorption line of atmosphere. All the criteria cause different velocity of the wave propagating into different medium of atmosphere and the change in the direction of the wave in order to follow the quickest path. This phenomenon is counting on Fermat's principle and Snell's law (Rueger, 1990; Kahmen & Faig, 1988).

Electromagnetic waves can be described by wavelength λ in m, frequency f in Hz and propagation velocity in m/s (Rueger, 1990). The relationship is defined based on:

$$\lambda = \frac{\bar{v}}{f}. \quad (1)$$

Therefore, the relationship of propagating velocity of wave into air v in m/s compared to the velocity of the same wave into vacuum c (= 29979245 m/s) can be defined by refractive index n.

$$n = \frac{c}{v}. \quad (2)$$

And refractivity N (without any particularly metric unit):

$$N = (n-1) \times 10^6. \quad (3)$$

In order to achieve the optimum performance over refractivity for distance measurements, it is essential to correct the wavelength of the radiation for the refractive index of air. In order to do so, the refractive index must be known at least as well as the precision of $1-8\times10^8$ (Rueger, 1990).

$$\lambda_{vac} = n \cdot \lambda_{air}. \quad (4)$$

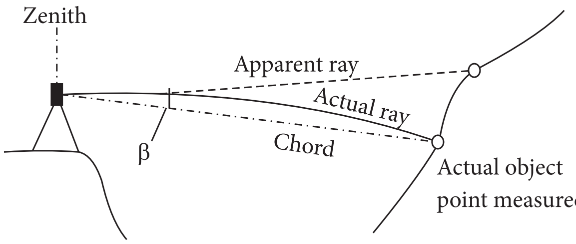

Figure 4. The actual ray is refracted, whereas the chord is the straight line (Friedli et al., 2019)

The main barrier of refractivity of air is its difficulty being accurately measured, so that there have been several re- measurements and different formulae to represent the dispersion curve of air, called angular refraction, by different scientists which will be discussed in the next section.

The Figure 4 shows the major effect of refraction over the signal. More importantly, it causes different intersection between the beam and the object surface at different epochs which introduces a certain deviation in the measured distances over the longer-range observations.

The prerequisite to correct the measured distances is to study refractive index of wave in the air. The main problem is the uncertainty in the average refractive index over the optical path due to non-uniformity and turbulence of the atmosphere.

For the sake of this, there are two techniques to obtain the value of the refractive index of air, firstly, by using the suitable sensors to precisely record the measurements of atmospheric pressure, air temperature and relative humidity of air and, secondly, the direct measurement using an interference refractrometer (Bonsch & Poulski, 1998). The latter technique has the benefit which is independent of variations of the air and the only calibration required is the initial relatively crude measurement of the length of the refractro meter cell (Birch & Downs, 1988).

One the other hand, there is more than one refractive index of interest, phase and group indices. Many EDM instruments use modulated light, and therefore require a knowledge of the group refractive index rather than the phase index (Ciddor, 1996; Brunner, 1984; Brunner & Rüeger, 1992). The below equation relates two indices:

$$n_g = n + \sigma\left(\frac{dn}{d\sigma}\right), \quad (5)$$

where n_g is group refractive index of light and infrared rays, n is phase refractive index, and σ is reciprocal wavelength (i.e., reciprocal of the vacuum wavelength is the wave number which is the inverse of wavelength into vacuum ($\sigma = 1/\lambda_{vac}$) in mm^{-1}). It is reported the group one is always smaller than the phase one of its individual frequencies (Rueger, 1990).

The relationship between group refractive index and the distance measurement is defined by (Angus-Leppan, 1989):

$$\bar{s} = \int (n_g - n_r)\, ds, \quad (6)$$

with n_r reference refractive index (i.e., an EDM determines the distance in relation to its internal reference refractivity), n_g the actual refractive index and the integration is performed along the length of line.

Finally, under the equation above, EDM correction w.r.t the group refractive index becomes (Angus-Leppan, 1989; Torge, 2001):

$$\bar{s} = s(n_g - n_r). \quad (7)$$

In order to fully comprehend corresponding correction via refractivity, pay particular attention to Figure 5.

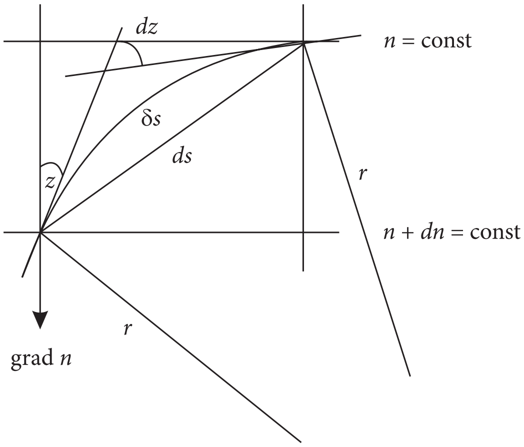

Figure 5. Effect of refraction of air on propagating wave (actual path length $\overline{s}$, the straight line s (chord), and z zenith angle) (Torge, 2001)

According to Eq. (7), it has been proved that when the atmospheric condition is neutral, mean value of end point measurements gives the correct reduction. This occurs in the hours soon after sunrise and around sunset, so these times are the most favorable for EDM (Angus-Leppan, 1989; Friedli et al., 2019).

To summarize, group refractive index is the key concern to find out the amount of change in correction for EDMs caused by atmosphere. In the next sections, an overview regarding the existing methods to determine this variable w.r.t the atmospheric changes are presented. Those methods to reveal the group refractive index are later nominated as the EDM correction models. It is important to state the analysis of atmosphere are here restricted to only considering air temperature, atmospheric pressure and relative humidity. The rest of atmospheric impacts (e.g., CO_2 content) is beyond of the scope of this work.

1. Revision of EDM correction models

To study the refractive index, numerous scientists have been taking different sets of calculations into serious account throughout the years. The first pure laboratory measurements of the refractivity of air were made in 1700, and it was estimated by Newton from astronomical refractions observations. Fairly accurate measurements initially became out a century later through the work of Arago and Biot. Since the 19th century onward, refractive index of air has been measured repeatedly in order to achieve better results (i.e., chronologically by scientists: Barrell & Sears, 1939; Edlen, 1953, 1966; Owens, 1967; Peck & Reeder, 1972; Jones, 1978, 1981; Matsumoto, 1982; Birch & Downs, 1988, 1993, 1994; Ciddor, 1996; Ciddor & Hill, 1999; Bonsch & Potulski, 1998, and the model adopted by International Association of Geodesy called Closed Formulae model in 1999 (International Association of Geodesy [IAG], 1999)).

Five of the existing EDM correction models have been selected here to gain the recovered knowledge of the atmospheric influences on EDMs: Edlen's latest work in 1966 (Edlen, 1966), the latest method of Birch and Downs (1994), Ciddor calculation in the year 1996 (Ciddor, 1996), two years after in 1998 the proposal of Bonsch and Potulski (1998), and Closed Formulae (adoption at International Association of Geodesy (IAG)) in the year 1999 (IAG, 1999). The reason for choosing them is to compare the findings of each scientist to the adoption of IAG and to yield to the decent improved EDM correction model.

1.1. Bengt Edlen (1966)

One of the very first attempt of refractivity computation belongs to Bengt Edlen, a Swedish scientist who revolutionized the world of optics by his attempts. His effort was devoted to two separate findings in 1953 and 1966. The latest version formula will be discussed here although several scientists onwards have done some modifications over Edlen's latest work (Edlen, 1966).

The following method of Edlen contains three main steps, the absolute refractivity, the dispersion formula, dependence on temperature and pressure, and the effects of variable contents such as water vapor, relating to relative humidity of air.

Dispersion equation: this equation has the capability to compute phase and group refractive index based on reciprocal wavelength within different modes of air (e.g., free of CO_2, water vapor of air (moist air), and carbon dioxide content of air which is not discussed here).

1. Phase index of refraction:

$$(n-1)_s \times 10^8 = 8342.13 + \frac{2406030}{130-\sigma^2} + \frac{15997}{38.9-\sigma^2}. \quad (8)$$

Concerning group refractive index according to Eq. (5):

$$(n-1)_s \times 10^8 = 8342.13 + \frac{2406030(130+\sigma^2)}{(130-\sigma^2)^2} + \frac{15997(38.9+\sigma^2)}{(38.9-\sigma^2)^2}. \quad (9)$$

2. Refractive index n_{tp} as a function of temperature t in °C and pressure p in torr:

$$(n-1)_{tp} = p\frac{(n-1)_s[1+p(0.817-0.0133t)\times 10^{-6}]}{720.775 \quad\quad 1+0.003661t}. \quad (10)$$

One of the important distinguishes between first two models, Edlen and modified one by Birch and Downs, is to have the better understanding of the applied atmospheric pressures in two different units. In order to convert torr into Pa, the constant 1 torr = 133.322 *Pa* shall be employed.

3. Finally, the effect of water vapor of the moist air depending on humidity n_{tpf} should be computed. As far as the moist air is composed of a partial pressure of water vapor f in torr component and the dry air at the same total pressure p in torr.

$$n_{tpf} - n_{tp} = -f(5.7224 - 0.0457\sigma^2)\times 10^{-8}. \quad (11)$$

The calculation of a partial pressure of water vapor *f* is clearly explained by Stone and Zimmerman (2001), Wexler and Greenspan (1971), Wexler (1976) and Marti and Mauersberger (1993).

1.2. Keith P. Birch and Michael J. Downs (1994)

Many revisions had been carried out over the studies of Edlen by different scientists in years afterwards. The most important modification which leads to the robust model belongs to Birch and Downs completed in the year 1994 although their findings had already resulted in different calculations models in some separate years (Birch & Downs, 1988, 1993). It is worth arguing the same structure in calculation of refractive index as Edlen's work was followed (Birch & Downs, 1994).

1. Dispersion equation: phase refractive index:

$$(n-1)_s \times 10^8 = 8342.54 + \frac{2406147}{130-\sigma^2} + \frac{15998}{38.9-\sigma^2}. \quad (12)$$

Accordingly, the group index of refraction:

$$(n-1)_s \times 10^8 = 8342.54 + \frac{2406147(130+\sigma^2)}{(130-\sigma^2)^2} + \frac{15998(38.9+\sigma^2)}{(38.9-\sigma^2)^2}. \quad (13)$$

2. Refractive index n_{tp} as a function of temperature t in °C and pressure p in Pa:

$$(n-1)_{tp} = p\frac{(n-1)_s}{96095.43}\frac{[1+p(0.601-0.00972t)\times 10^{-8}]}{1+0.003661t}. \quad (14)$$

3. Finally, n_{tpf} (partial pressure of water vapor f in Pa).

$$n_{tpf} - n_{tp} = -f(3.7345 - 0.0401\sigma^2)\times 10^{-10}. \quad (15)$$

1.3. Philip E. Ciddor (1996)

Ciddor was the other scientist who has developed a new set of equations based on more recent equations for density and dispersion in the visible and near infrared regions. He believed the most useful of the formerly indicated models are those to apply larger wavelength range, 230 nm – 1690 nm, in order to better fit in the near infrared domain, the domain which most of the 3D laser scanners, total stations and EDMs is functioning (Ciddor, 1996; Ciddor & Hill, 1999). Furthermore, the instruction suggested by Ciddor is quite different from two models above.

The subsequent steps are, including computing phase and group refractive index (i.e., standard air and water vapor), determining their densities and the relevant compressibilities and calculation of refractive index based on standard and moist air.

Phase refractive indices of standard air n_{axs} and of water vapor n_{ws}:

$$10^8(n_{as}-1) = \frac{5792105}{(238.0185-\sigma^2)} + \frac{167917}{(57.362-\sigma^2)}; \quad (16)$$

$$10^8(n_{ws}-1) = cf(295.235 + 2.6422\sigma^2 - 0.03238\sigma^4 + 0.004028\sigma^6), \quad (17)$$

with cf the correction factor (= 1.022). Concerning the group refractive indices:

$$10^8(n_{as}-1) = \frac{5792105(238.0185+\sigma^2)}{(238.0185-\sigma^2)^2} + \frac{167917(57.362+\sigma^2)}{(57.362-\sigma^2)^2}; \quad (18)$$

$$10^8(n_{ws}-1) = cf(295.235 + 7.9266\sigma^2 - 0.1619\sigma^4 + 0.028196\sigma^6). \quad (19)$$

Density of the dry air r_{axs}, r_a and of the moist air r_{ws}, r_w components with corresponding values of compressibility Z:

$$\rho_{axs} = \rho_{ws} = \left(p\frac{M_a}{ZRT}\right)\left(1 - x_w\left(1-\frac{M_w}{M_a}\right)\right); \quad (20)$$

$$\rho_a = pM_a(1-x_w)/ZR; \quad (21)$$

$$\rho_w = pM_w x_w / ZR \quad (22)$$

and compressibility Z:

$$Z = 1 - \left(\frac{p}{T}\right)[a_0 + a_1 t + a_2 t^2 + (b_0 + b_1 t)x_w + (c_0 + c_1 t_w)x^2] + \left(\frac{p}{T}\right)^2(d + ex_w), \quad (23)$$

where p is pressure in Pa, T is temperature in K, and x_w is the water vapor component of air depending on humidity, M_a is molar mass of dry air containing x_c ppm of CO_2, and M_w is molar mass of water vapor both in kg/mol, Z is compressibility of pure water vapor and standard dry air, and R is the gas constant in $\mathrm{Jmol^{-1}\,K^{-1}}$. All definitions and constants are defined by Ciddor.

Evaluate refractive index of moist air n_{prop} including dry air and water vapor component, by the equation below:

$$n_{prop} - 1 = \left(\frac{\rho_a}{\rho_{axs}}\right)(n_{axs}-1) + \left(\frac{\rho_w}{\rho_{ws}}\right)(n_{ws}-1). \quad (24)$$

1.4. Gehard Bonsch and E. Potulski (1998)

One of the very recent alterations over the findings of Edlen has been carried out right after Ciddor's job in 1998 by Bonsch and Potulski. The instruction for calculation is very much near to Edlen and Birch and Downs but different constants proposed to recalculate and update the results (Bonsch & Potulski, 1998).

1. Dispersion equation: phase refractive index:

$$(n-1)_s \times 10^8 = 8091.37 + \frac{2333983}{130-\sigma^2} + \frac{15518}{38.9-\sigma^2}. \quad (25)$$

Accordingly, the group index of refraction:

$$(n-1)_s \times 10^8 = 8091.37 + \frac{2333983(130+\sigma^2)}{(130-\sigma^2)^2} + \frac{15518(38.9+\sigma^2)}{(38.9-\sigma^2)^2}. \quad (26)$$

2. Refractive index n_{tp} as a function of temperature t in °C and pressure p in Pa:

$$(n-1)_{tp} = p\frac{(n-1)_s[1+p(0.5953-0.009876t)\times 10^{-8}]}{93214.6 \quad 1+0.003661t}. \quad (27)$$

3. Finally, n_{tpf} (Partial pressure of water vapor f in Pa).

$$n_{tpf} - n_{tp} = -f(3.8020 - 0.0384\sigma^2)\times 10^{-10}. \quad (28)$$

1.5. Closed Formulae (International Association of Geodesy Adoption) (1999)

The Closed Formulae is adopted at the 22nd General Assembly in Birmingham by International Association of Geodesy (IAG) for computation of group and phase refractive index of air for EDM in the year 1999 which can be an ideal hypothesis for this research and a suitable tool for comparisons (IAG, 1999).

The steps are calculation of group or phase refractivity under standard air condition, partial pressure of water vapor at dew point temperature and finally refractive index at given temperature T in K, pressure p and water vapor pressure e in mbar (1 mbar = 1 hPa = 1 Pa / 100) corresponding to the phase or group index:

1. Dispersion equation: computation of phase refractivity:

$$N = 287.6155 + \frac{4.8866}{3\lambda^2} + \frac{0.068}{5\lambda^4}, \quad (29)$$

where λ is wavelength in mm. Concerning group refractivity:

$$N = 287.6155 + \frac{4.8866}{\lambda^2} + \frac{0.068}{\lambda^4}. \quad (30)$$

2. Determination of partial pressure of water vapor e at dew point temperature t_{dp} in °C:

$$e = 6.11^{\left(7.45t_{dp}\right)/\left(235+t_{dp}\right)}. \quad (31)$$

Dew point temperature is the temperature at which the air can no longer hold all the water vapor which is mixed with it, and some of the water vapor must condense into liquid water. The dew point is always lower than or equal to the air temperature, and it is calculated by $t_{dp} = t - ((100 - RH)/5)$.

3. At the end, calculation of refractive index n_g and refractivity N_L corresponding to phase and group indices:

$$N_L = \frac{273.15Np}{1013.25T} - \frac{11.27e}{T}; \quad (32)$$

$$n_g = 1 + N_L 10^{-6}. \quad (33)$$

At the end, the introduced deviation by the variation in atmospheric elements on EDM is computed by the change in group refractive index into ppm scale within defined interval of atmospheric changes according to Eq. (7). The correction for each EDM model is calculated and graphically and numerically compared throughout the wide range of meteorological domains in order to reveal the improved EDM correction model.

2. Results and discussions

The impact of refraction on range measurement beam from EDM nominated as group refractive index results in refracted wavelength. Therefore, the method is to study this index and to compare the results of correction in five selected EDM correction models in three different categories of atmosphere. The assumed domain of analyze is –20 °C – 40 °C, 600–1100 hPa, and 0–100% for air temperature, atmospheric pressure and relative humidity of air, respectively. Those were introduced due to the applicability of certified surveying instrument (Ciddor, 1996) and possessing the better approximation of the real changes in the atmosphere. Additionally, the changes are computed within 10 °C, 5 hPa and 10% change interval in each element of atmosphere. Each category contains four demonstrations, basically, (i) trend of group refractive index of air in the entire domain, (ii) correction in ppm within defined interval, (iii) comparison of corrections with Closed Formulae model, and (iv) behavior of EDM correction compared to the change in measured distance. As a clear result, at the end, the entire improvement of atmospheric modelling for EDM in comparison with real data collected will be concluded.

For the understandable illustration, each meteorological element is individually investigated in the graphical and tabular manner.

In practice, to compute the correction of EDM, following steps are common in all present models:

1) Calculate the group refractive index via dispersion equation with the help of relevant EDM wavelength (e.g., 915 nm in near infrared region) into different modes of atmosphere (i.e., standard air (free from CO_2), and moist air (water vapor)).
2) Determine the partial water vapor pressure based on relative humidity of air which is one of the main variables in this study.
3) Compute the group refractive index based on the atmospheric pressure, air temperature, and partial water vapor pressure.
4) At last, determine EDM correction in ppm by the difference of group refractive index in every epoch of atmospheric changes according to Eq. (7).

2.1. Air temperature

The temperature range analyze is restricted to –20 °C – 40 °C. Moreover, the atmospheric condition of Stuttgart in Germany is supposed, the average height of 247 m above the sea level corresponding to the air pressure of 983.9272 hPa with the annual mean relative humidity 72%.

1. Group refractive index of air:

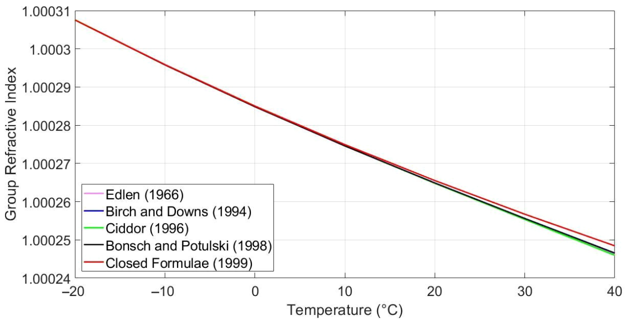

Figure 6. Effect of temperature on group refractive index of air calculated in five EDM correction models

All the models experience a decrease in group refractive index, by the rise in temperature (Figure 6). However, this drop is in different rates among the models. For example, the decrease rate in Ciddor model is slightly sharper than Closed Formulae model, concerning different structure in calculation.

2. EDM corrections in PPM:

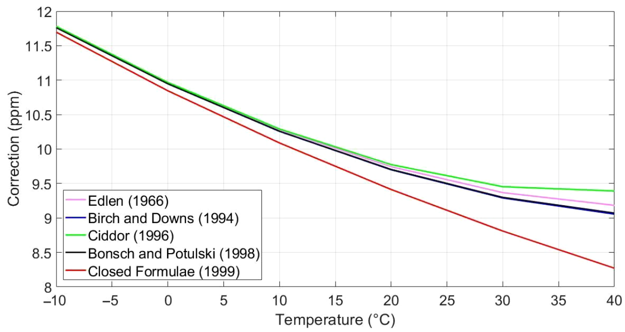

Figure 7. EDM corrections in every interval of 10 °C

The corrections in Edlen, Birch and Downs, Ciddor, and Bonsch and Potulski model are relatively close (Figure 7); however, there is a gap between those findings and Closed Formulae model which reaches to nearly 1 ppm within the last interval change (i.e., pay particular attention to Figure 8). This difference comes from the different calculation of partial water vapor pressure in Eq. (31) and Stone and Zimmerman recommendation in 2001 and applying different constants in dispersion equation in each model.

The important outcome is that the value of correction in every 10 °C change varies from 8 ppm to 11.5 ppm. Table 1 shows the exact values of EDM corrections for the rise of 10 °C in the atmosphere in each model.

To accurately explain, if the environment gets warmer by 10 °C, from 0 °C to 10 °C, the measured distance is positively affected by 10 ppm in Edlen correction model. It can be inferred every change in centigrade brings approximately +1 ppm correction.

The above values are not identical in all equal interval change, meaning that the change in warmer temperature above zero gives lower numbers of ppm than colder temperatures below zero (e.g., on the average 9 ppm between 30 °C and 40 °C, while 11 ppm between –20 °C and –10 °C). Therefore, there is no fixed value to correct the distance by every single change in temperature (i.e., the amount of correction strongly depends on at what temperature the change occurs (Table 2)).

On the other hand, the differences between models reach to the maximum amount of a ppm in higher temperature. Hence, it is highly recommended to prioritize the EDM correction models at those temperatures (Table 2).

3. Comparison of corrections with Closed Formulae model:

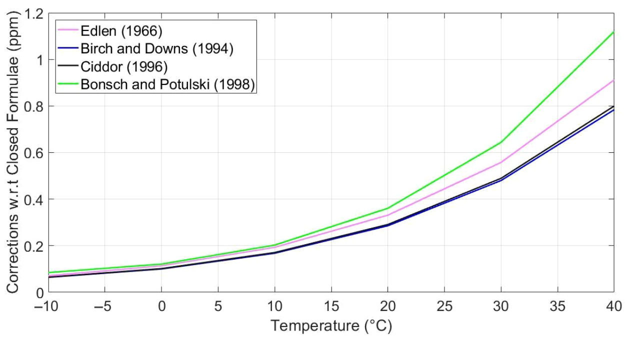

Figure 8. Comparison of EDM corrections w.r.t Closed Formulae model

To compare the results with Closed Formulae model, the differences increase by the rise in temperature so that there is no broad gap between the models from –10 °C to circa. 15 °C (i.e., since the air becomes hotter, differentiation between EDM correction models plays a more

Table 1. EDM corrections in every 10 °C interval (ppm)

Temperature Change (°C)	Edlen	Birch and Downs	Ciddor	Bonsch and Potulski	Closed Formulae
–20 to –10	11.76	11.76	11.78	11.76	11.69
–10 to 0	10.95	10.94	10.96	10.94	10.84
0 to 10	10.28	10.25	10.29	10.25	10.08
10 to 20	9.74	9.69	9.77	9.7	9.41
20 to 30	9.36	9.28	9.45	9.29	8.81
30 to 40	9.18	9.05	9.39	9.07	8.27

important role). Table 2 shows the maximum difference might occur in calculation in case of using different EDM models.

Table 2. Differences in EDM corrections w.r.t Closed Formulae model (ppm)

Temperature Change (°C)	Edlen	Birch and Downs	Ciddor	Bonsch and Potulski
–20 to –10	0.07	0.06	0.08	0.06
–10 to 0	0.11	0.1	0.12	0.1
0 to 10	0.19	0.16	0.2	0.17
10 to 20	0.33	0.28	0.36	0.29
20 to 30	0.55	0.48	0.64	0.48
30 to 40	0.91	0.79	1.11	0.8

The numerical values show the highest difference belongs to Ciddor model, whereas closest approximation to Closed Formulae model is Birch and Downs's presentation although all numbers are less than a ppm (i.e. it varies from 0.06 ppm to 1 ppm). Thus, in case of any unintentional exchange between EDM correction models, it is expected maximally 1 ppm difference will be added in the calculation especially in higher temperature, concerning the rise of 10 °C in the atmosphere.

4. Correction vs. measured distance:

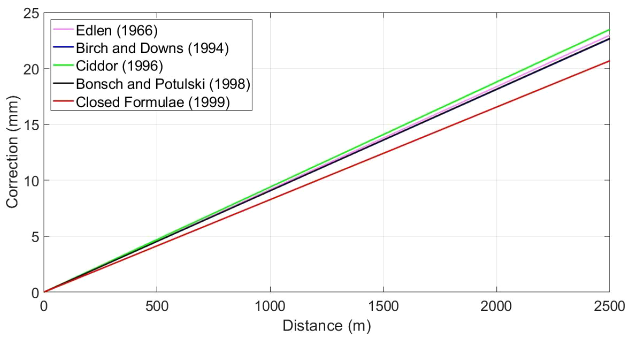

Figure 9. Correction vs. measured distance

Clearly, there is a linearly direct relationship between measured distance and its correction. Figure 9 compares the longer distance in meters EDM can measure, the more correction in millimeters is employed (i.e., it reaches to 2.2 cm by the rise of 10 °C in the atmosphere at the target range measured of 2500 m). Additionally, the changes between EDM models in the distances exceeding approximately 750 m measurement is more than a ppm.

2.2. Atmospheric pressure

The assumed domain analysis for atmospheric pressure is 600 hPa as the lowest and the highest 1100 hPa. The rest of hypothesis is based on Stuttgart atmospheric condition.

1. Group refractive index of air:

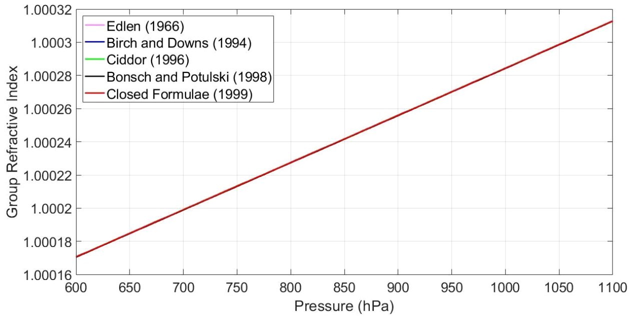

Figure 10. Effect of pressure on group refractive index of air calculated in EDM correction models

According to Figure 10, the group refractive index by the rise in pressure is linearly increasing. Besides, no significant differences between models will be observed (Figure 12).

2. EDM corrections in PPM:

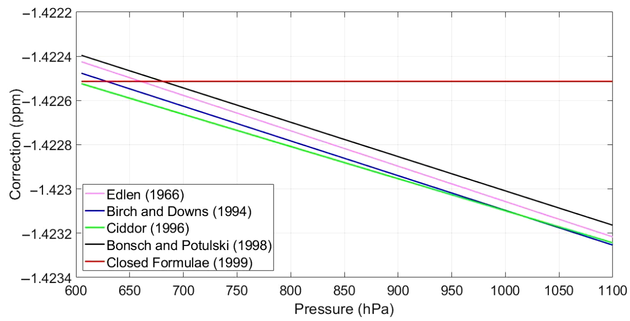

Figure 11. EDM corrections in every interval of 5 hPa

Figure 11 shows its correction remains constant in the predefined domain of pressure (i.e., the group refractive index changes by the equal value in each 5 hPa pressure interval). Additionally, the behavior of Closed Formulae model is not comparable with the other four models. Even though the gap between its corrections and four other models is considerable, this does not affect the correction in the order of ppm. Therefore, the amount of correction in all models by 5 hPa increase is assumed 1.4 ppm (i.e., it is expected 1 hPa increase results in –0.28 ppm correction).

Secondly, the corrections by the increase in atmospheric pressure are negative, meaning that in contrast to temperature corrections which add measured distances, here the corrected distances are less than measured distances.

To sum up, it can be interpreted there is no such a serious requirement to distinguish EDM correction models due to minor differences 8×10^{-4} ppm between models, and every change in pressure results in the equal correction in ppm, unlike air temperature variation.

3. Comparison of corrections with Closed Formulae model:

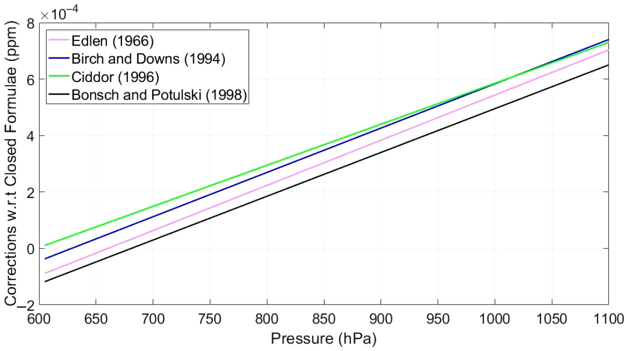

Figure 12. Comparison of EDM corrections w.r.t Closed Formulae model

The diagram proves the EDM correction models can freely be replaced with each other due to the very small difference between corrections in each interval.

4. Correction vs. measured distance:

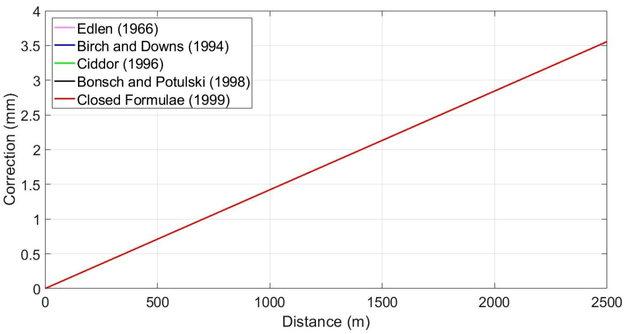

Figure 13. Correction vs. measured distance

Normally, the longer range EDM measures, the larger correction shall be applied (Figure 13). And there is no significant gap between correction models in the entire domain of pressure analyze.

From numerical perspective, while having 5 hPa increase in the atmosphere, the correction for measured distance at 2500 m is 3.5 mm. These values in all correction models are identical in the order of millimeter.

2.3. Relative humidity of air

The entire domain of relative humidity in the air 0–100% will be considered which will also prove the change of 100% in relative humidity, far from reality in atmosphere, has the equal value of correction as 1 hPa increase in atmosphere (Figure 14). Thus far, the rise of 1 °C and 1 hPa brings approximately 1 ppm and –0.28 ppm change in EDM correction, respectively.

The more humid air gets, the less refractivity on wave can occur, like temperature analyze; however, the rate of this drop is considerably lower than temperature decrease.

It is seen the behavior of Closed Formulae model is not comparable with the other models which this gap highly links to different calculation method of partial water vapor pressure using dew point temperatures according to Eq. (31) in the models of Stone and Zimmerman (2001) and Wexler (1976).

1. Group refractive index of air:

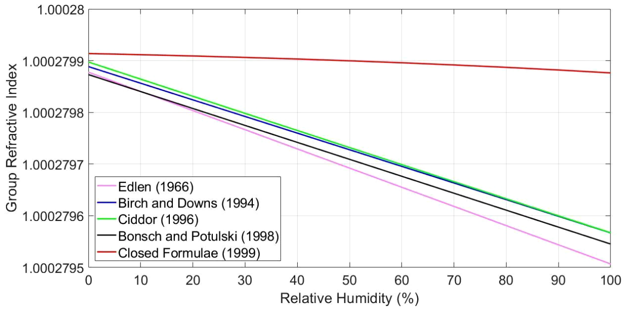

Figure 14. Effect of relative humidity on group refractive index of air calculated in EDM correction models

2. EDM corrections in PPM:

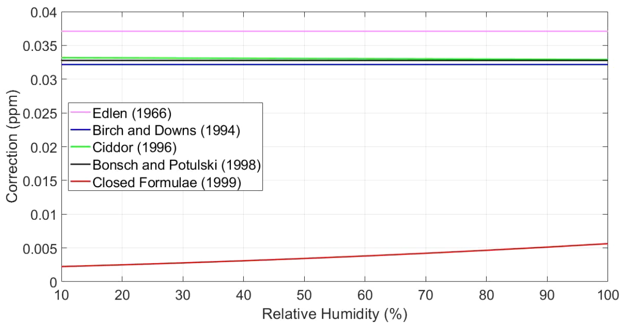

Figure 15. EDM corrections in every interval of 10%

It is obvious that the change in group refraction index is constant. Therefore, the equal value of correction for every single change in RH should be added to measured distances, according to Figure 15. This value is small enough in comparison with two other effects of atmosphere (i.e., 0.03 ppm concerning every 10% increase in relative humidity). It is anticipated within 100% change, it reaches to 0.3 ppm, approximately equal to the correction of 1 hPa change. Furthermore, the differences between models are insignificant (Figure 16).

3. Comparison of corrections with Closed Formulae model:

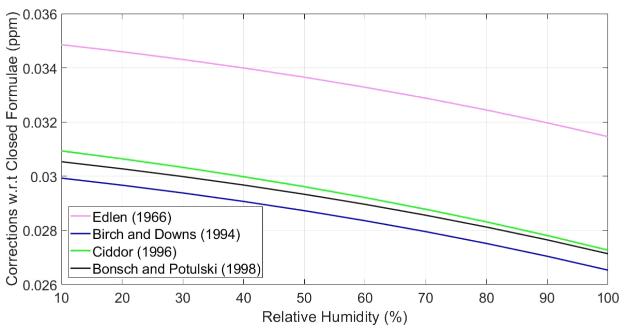

Figure 16. Comparison of EDM corrections in each model w.r.t Closed Formulae model

In order to compare the result with adoption of IAG, it is remarkable that the numerical values between models maximally reach to 3×10^{-2} ppm.

Although the correction of humidity is considerably lower than pressure, the fluctuation between EDM models in humidity analyze is higher. It is meant distinguish between EDM models in humidity change analyze is more important than pressure change analyze in more accurate surveying projects.

4. Correction vs. measured distance:

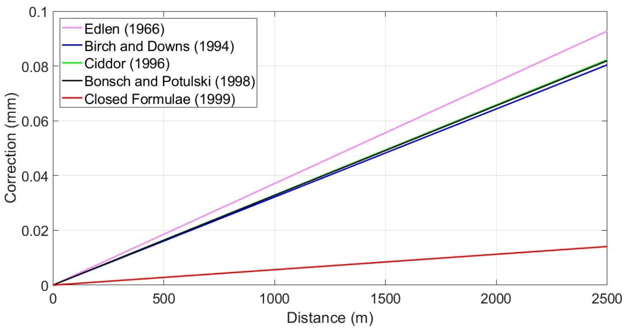

Figure 17. Correction vs. measured distance

It is expected this results in the linear direct connection between measured distance and corresponding correction like above. Also, it is feasible to observe the effect of humid air at the range of 2500 m is not larger than 0.1 mm, given the rise of 10% in RH (Figure 17).

From numerical values, it is visible the correction by humidity of air drops for same distance domain analyze, from centimeter in temperature and millimeter in pressure analyze to lower. In this domain, the correction from Closed Formulae model is approximately eightfold less than other models. The main reason behind is the different method to compute partial pressure of water vapor pressure (Eq. (31)).

2.4. Improvement of atmospheric modelling on EDM

This part includes two important arguments, simulated data analysis and comparison with real data analysis.

The first argument is EDM corrections will be modelled in such a way that all the effects of atmosphere in a simulated manner (e.g., 10 °C, 5 hPa, and 10% change in air temperature, atmospheric pressure, and relative humidity of air, respectively) simultaneously occur. This is the real case scenario which most of the surveyors are dealing with.

To better address the issue, Eq. (32) is assumed first. By partials differentials, and assuming the standard air condition, t = 15 °C, p = 1007 hPa, e = 13 mbar and N = 304.5 defined by Rueger (1990), the following equation is obtained:

$$dn \times 10^6 = -0.99dt + 0.28dp - 0.039de. \quad (34)$$

The coefficient are those already calculated by the unit change in atmosphere in tables and figures above (i.e., to further analyze, pay more attention to Table 3) (Bamford, 1980).

Accordingly, for minus temperature (below zero):

$$-dn \times 10^6 = 1.11dt - 0.28dp + 0.03de. \quad (35)$$

And positive temperature (above zero),

$$-dn \times 10^6 = 0.93dt - 0.28dp + 0.039de. \quad (36)$$

Therefore, based on the equations, in order to obtain the exact change in correction caused by multiple atmospheric effects, it is only required to multiple the number of changes with corresponding values.

In summary, the expected corrections corresponding to unit change in each atmospheric parameter are:

Table 3. EDM corrections by unit change in atmospheric parameters plus maximum difference between correction models (ppm)

Unit Change in Atmospheric Parameters		EDM Corrections	Maximum Difference between Models
Temperature (1 °C)	Below zero	1.11	0.012
	Above zero	0.93	0.115
Pressure (1 hPa)		–0.28	0.0001
Humidity (1%)		0.003	0.003

Consequently, the rise of 1 °C in temperature brings 1.11 ppm change in correction in case temperature changes below zero, whereas the identical increase above zero leads to lower change in correction approximately 0.93 ppm. Regarding two other elements of atmosphere, the entire increase in RH has the equal impact but in the opposite direction as the rise of 1 hPa in the environment, as discussed above.

Given the Eq. (34), for instance, the rise of 15 °C above zero, fall of 2 hPa in atmospheric pressure, and increase of 20% in RH during the measurement time span causes

$$15\,°\mathrm{C} \times (0.93\ \mathrm{ppm}) - 2\ \mathrm{hPa} \times (-0.28\ \mathrm{ppm}) + 20\% \times (0.003\ \mathrm{ppm}) = 14.57\ \mathrm{ppm}$$

deviation on EDM, and the EDM models maximally differs by

$$15\ °\mathrm{C} \times (0.115\ \mathrm{ppm}) - 2\ \mathrm{hPa} \times (-1 \times 10^{-4}\ \mathrm{ppm}) + 20\% \times (3 \times 10^{-3}\ \mathrm{ppm}) = 1.78\ \mathrm{ppm}$$

(pay particularly attention to the sign of each applied correction).

Therefore, the main influence of deviation comes from the temperature change, so the accurate determination of temperature is seriously required (Rueger, 1990). In addition, in the desired accuracy of ppm or better, it is crucial to be aware of the differences between EDM correction models.

On the other hand, in order to confirm the results obtained from simulated analysis, the field work measurement was carried out on 11th of March 2020 in the region close to Stuttgart, called Urbach, and the findings via distribution of four Greisinger thermo-, barometers sensors called GTD1100 (Greisinger GmbH Ragenstauf, Germany) during measurements were between 9 °C and 16 °C for air temperature, the change of atmospheric pressure between 984.4 hPa and 985.3 hPa, and relative humidity ranged from 55% to 85%. Therefore, the corrections based on the five proposed models are depicted in the following Table 4.

Table 4. EDM corrections w.r.t atmospheric changes calculated in each model (ppm)

Atmospheric Parameters	Edlen	Birch and Downs	Ciddor	Bonsch and Potulski	Closed Formulae
Temperature (°C)	6.81	6.79	6.83	6.8	6.62
Pressure (hPa)	–0.24				
Relative Humidity (%)	0.18	0.16	0.16	0.15	0.01

To numerically verify, the increase of 7 °C in temperature, 0.9 hPa in pressure and 30% in relative humidity brings nearly 7 ppm, –0.24 ppm and 0.16 ppm change in EDM correction, respectively. The highest effect appears from temperature variation, as discussed before; however, least atmospheric effect is from relative humidity variation. Furthermore, the difference between EDM models is not notable in the order of ppm.

The above assumption which holds every single change in temperature above zero changing the correction by 0.93 ppm in Table 3 reduced to 0.67 ppm in the real data analysis. This difference appears due to two matters: first the rest of atmospheric effects which have been neglected in this research can play the major role, and second it is the result of different assumption in atmospheric pressure and relative humidity (i.e., Urbach atmospheric pressure (e.g., 984.85 hPa) is adjusted higher than simulated pressure assumed for Stuttgart (e.g., 983.9272 hPa)).

As a conclusion, in the identical condition of temperature change in atmosphere, the rise in atmospheric pressure *negatively* affects the correction in ppm, while, in case of drop in atmospheric pressure, the correction caused by temperature variation is expected to be *positively* changing (i.e., it is vital to take the sign of applied correction in Table 3 and 4 into serious account). Also, for the same RH fluctuation, the rise in temperature and pressure changes the correction of humidity from expected value of 0.09 ppm based on Table 3 to 0.18 ppm since the effect of temperature is positively rising and considerably larger than pressure influences. Also, the other atmospheric mentioned elements are the means to change these values.

Conclusions

Nowadays, the highly accurate geodetic measurements are quite demanding by project managers. The accuracy of EDM like any other types of geodetic measurements are certainly affected by different variables especially atmospheric changes. This research aimed to reveal the developing of modelling for atmospheric effects on long range EDM corrections. The interactions of three constitutions of atmosphere including air temperature, atmospheric pressure and relative humidity of air on EDM were considered in this current work although several other elements into atmosphere are influencing the direction of laser beam measuring.

Therefore, it has clearly been witnessed the determination of temperature is very critical. It is recommended by Rueger to be measured accurately at both terminals of a line and the group refractive index calculated for both terminals and the mean taken. Even so, the mean value of the group refractive index generally does not represent the prevailing integral value over the wave path better than 1 ppm, and for more accurate surveying measurements than 0.1 ppm, EDM correction models shall be distinguished.

There have been several arguments recommended for further investigations as future works. Firstly, the differences between simulated and real data analysis have illustrated they have been other elements of atmosphere such as content of carbon dioxide, oil vapor of air and the effects of absorption line impacting the results. Therefore, it arises the enough clue to be investigated for more accurate than ppm accuracy in surveying and 3D visualization works. Secondly, the research depicted finding the appropriate model to determine the partial water vapor pressure, highly depending on relative humidity, in geodetic measurements is still the unanswered question despite the fact each EDM correction model employs different calculations leading to the deviation in final results. Thirdly, the study of refractivity on vertical and horizontal angle measurements has the potential for future research in order to achieve the accurate 3D point coordinates. Fourthly, all discussions were validated for EDM observations and other geodetic instruments functioning in the range of light or near infrared domain of EM spectrum; however, in case of having collected data by other instruments in the other domain of EM spectrum such as ranging radar, the scenario would completely be different. Therefore, it is very important to find out the behavior of EM waves, refractivity and reflectivity of wave, as a function to height and other elements throughout dry and wet troposphere and ionosphere to estimate their corrections.

References

Angus-Leppan, P. V. (1989). Geodetic refraction. In *Geophysics. Encyclopedia of Earth Science*. Springer. https://doi.org/10.1007/0-387-30752-4_59

Barrell, H., & Sears, J. E. (1939). The refraction and dispersion of air for the visible spectrum. *Journal of Philosophical Transaction of the Royal Society of London*, *238*(786), 1–64. https://doi.org/10.1098/rsta.1939.0004

Birch, K. P., & Downs, M. J. (1988). The results of a comparison between calculated and measured values of the refractive index of air. *Journal of Physics E: Scientific Instruments*, *21*(7), 694–695. https://doi.org/10.1088/0022-3735/21/7/015

Birch, K. P., & Downs, M. J. (1993). An updated Edlen equation for the refractive index of air. *Journal of Metrologia*, *30*(3), 155–162. https://doi.org/10.1088/0026-1394/30/3/004

Birch, K. P., & Downs, M. J. (1994). Correction to the updated Edlen equation for the refractive index of air. *Journal of Metrologia*, *31*(4), 315–316. https://doi.org/10.1088/0026-1394/31/4/006

Bamford, G. (1980). *Geodesy* (4th ed.). Clarendon Press.

Bonsch, G., & Potulski, E. (1998). Measurement of the refractive index of air and comparison with modified Edlen's formulae. *Journal of Metrologia*, *35*(2), 133–139. https://doi.org/10.1088/0026-1394/35/2/8

Brunner, F. K. (1984). *Geodetic Refraction: Effects of electromagnetic wave propagation through the atmosphere*. Springer-Verlag.

Brunner, F. K., & Rüeger, J. M. (1992). Theory of the local scale parameter method for EDM. *Bulletin Geodesique*, *66*, 355–364. https://doi.org/10.1007/BF00807420

Ciddor, P. E. (1996). Refractive index of air: New equation for visible and near infrared. *Journal of Applied Optics*, *35*, 1566–1573. https://doi.org/10.1364/AO.35.001566

Ciddor, P. E., & Hill, R. J. (1999). Refractive index of air. 2. Group index. *Journal of Applied Optics*, *38*, 1663–1667. https://doi.org/10.1364/AO.38.001663

Edlen, B. (1953). The dispersion of standard air. *Journal of the Optical Society of America*, *43*(5), 339–344. https://doi.org/10.1364/JOSA.43.000339

Edlen, B. (1966). The refractive index of air. *Journal of Metrologia*, *2*(2), 71–80. https://doi.org/10.1088/0026-1394/2/2/002

Friedli, E., Presl, R., & Wieser, A. (2019, May). Influence of atmospheric refraction on terrestrial laser scanning at long range. In *Proceedings of 4th Joint International Symposium on Deformation Monitoring (JISDM)*. Athens, Greece.

International Association of Geodesy. (1999). *IAG Resolutions at the XXIIth General Assembly in Birmingham*.

Jones, F. E. (1978). The air density equation and the transfer of the mass unit. *Journal of Research of the National Bureau of Standards*, *83*(5), 419–428. https://doi.org/10.6028/jres.083.028

Jones, F. E. (1981). The refractivity of air. *Journal of Research of the National Bureau of Standards*, *86*(1), 27–32. https://doi.org/10.6028/jres.086.002

Kahmen, H. & Faig, W. (1988). *Surveying*. de Gruyter. https://doi.org/10.1515/9783110845716

Maar, H., & Zogg, H. M. (2014). *WFD – Wave Form Digitizer technology, white paper*. Leica Geosystems EDM Technology.

Marti, J. M., & Mauersberger, K. (1993). A survey and new measurements of ice vapor pressure at temperatures between 170 and 250K. *Geophysical Research Letters*, *20*(5), 363–366. https://doi.org/10.1029/93GL00105

Matsumoto, M. (1982). The refractive index of moist air in the 3-μ region. *Metrologia*, *18*(2), 49–52. https://doi.org/10.1088/0026-1394/18/2/001

Owens, J. C. (1967). Optical refractive index of air: Dependence on pressure, temperature, and composition. *Applied Optics*, *6*(1), 51–59. https://doi.org/10.1364/AO.6.000051

Peck, E. R., & Reeder, K. (1972). Dispersion of Air. *Journal of the Optical Society of America*, *62*(8), 958–962. https://doi.org/10.1364/JOSA.62.000958

Rueger, J. M. (1990). *Electronic distance measurement* (3rd ed.). Springer-Verlag. https://doi.org/10.1007/978-3-642-97196-9

Stone, J. A., & Zimmerman, J. H. (2001). *Index of refraction of air*. The National Institute of Standards and Technology (NIST).

Torge, W. (2001). *Geodesy* (3rd ed.). Walter de Gruyter.

Wexler, A. (1976). Vapor pressure formulation for water in range 0 to 100 °C. A revision. *Journal of Research of the National Bureau of Standards*, *80A*(5–6), 775–785. https://doi.org/10.6028/jres.080A.071

Wexler, A. G., & Greenspan, L. (1971). Vapor pressure equation for water in the range 0 to 100 °C. *Journal of Research of National Bureau of Standards*, *75A*(3), 213–245. https://doi.org/10.6028/jres.075A.022