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Anomalous atmospheric refraction and comments on "fast and accurate determination of astronomical coordinates …" (Balodimos et al. 2003, Survey Review 37(290):269-275)

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ABSTRACT

Balodimos et al. (2003, Survey Review 37(290):269-275) presented astrogeodetic instrumentation for the determination of astronomical coordinates, and stated an accuracy of ±0.01″ would be achieved within few hours observation time. However, these authors did not address anomalous atmospheric refraction, the effect of which is relevant for any accurate determination of astronomical latitude Φ and longitude Λ. This correspondence briefly reviews anomalous refraction and its effect on astrogeodetic methods, by first defining anomalous refraction, describing its origins, summarising results of theoretical and empirical studies, and giving ways to mitigate its effect. This demonstrates that anomalous refraction represents a major obstacle for determining astronomical coordinates (Φ,Λ) at the 0.01″ accuracy level from just a few hours of star observations, as claimed by Balodimos et al. (2003).

INTRODUCTION

Balodimos et al. (2003) published a paper in Survey Review (37(290): 269-275) titled "*Fast and accurate determination of astronomical coordinates Φ, Λ and azimuth, using a total station and GPS receiver*". This work, hereafter abbreviated to BAL03, is among the first to present modernised astrogeodetic instrumentation for the determination of astronomical coordinates (astronomical latitude Φ and longitude Λ) and vertical deflections, and among the first astrogeodetic works of that makes use of highly accurate star positions from the Tycho-2 catalogue (Høg et al. 2000) that resulted from the Hipparcos satellite astrometry mission (ESA 1997).

BAL03 describe the use of a high-accuracy total station to measure directions to stars at about 5° to 30° zenith distance. The authors observe pairs of transiting stars and apply the Sterneck method (Mueller 1969, p.470) for Φ determination. For Λ determination, BAL03 apply the Meyer-method (Mueller 1969, p.504) and utilise the GPS-receiver for automated time-epoch registration. BAL03 collected 80 to 120 repeated observations for each star within a time window of "*several minutes around the meridian transit*" and apply this strategy to about 12 star pairs, yielding a total of "*2000 to 3000 individual time and angle measurements*" to determine (Φ,Λ) at one station. In their section on data reduction, BAL03 provide following key information on the (Φ,Λ) accuracy:

(i) the combination of all repeated observations of a star and a polynomial regression "*greatly reduces random (pointing) errors*" and allows determination of zenith angles to 0.3″ accuracy, and

(ii) using 12 star pairs, "*properly weighted with their respective errors*", yields an RMS (root mean square) error of the mean Φ of the order of ±0.01″; likewise for Λ with 24 star pairs.

For a single field station, BAL03 reported mean accuracy values of ±0.011″ for Φ and ±0.016″ for Λ. These values originated from four hours of field work, carried out during one night. BAL03 state in their abstract that "*an accuracy of* $\sigma_\Phi = \sigma_\Lambda$ = ±0.01″ [] *may be achieved for the determination of the astronomical coordinates* []" and repeat the same accuracy numbers in their introduction.

The motivation for this correspondence is because BAL03 do not fully substantiate their $\sigma_\Phi = \sigma_\Lambda$ = ±0.01″ accuracy statement. In any measurement science, accuracy can be a bold claim as it indicates that systematic errors are also low, whereas precision is often the better descriptor. Also, BAL03 do not comment on correlations between repeatedly observed zenith angles, especially over a relatively short time-span of few hours over one night. These can be caused by, e.g., (i) anomalous atmospheric refraction, (ii) residual systematic instrumental errors, and (iii) environmental influences (e.g., wind, temperature, micro-seismicity) on their instrument set-up. Though not stated explicitly, BAL03 apparently assume uncorrelated observational errors that can be reduced with the square-root of observations, down to the ±0.01″-level. However, this propagation does not apply in the presence of correlated or non-white-noise errors.

The purpose of this correspondence is to provide a short review of anomalous atmospheric refraction (also known as zenith refraction or atmospheric refraction anomalies) with regard to BAL03. This effect is relevant for any accurate ground-based astrogeodetic method or instrumentation, but was not addressed in BAL03. A good point on the relevance of refraction anomalies was made in 1967 by Karl Ramsayer: "*It is well known that the accuracy of the astronomical determination of latitude and longitude [] is limited by the accuracy of the determination of astronomical refraction. This is accepted as an inevitable fact, and has led to the general opinion that for precise astronomical measurements it is absolutely necessary to observe during several nights to reduce the influence of refraction anomalies*" (Ramsayer 1967, p. 260).

Another unmentioned effect that becomes relevant at the 0.01″ accuracy-level is tidal variation of the plumbline. However, this effect is not discussed here; instead we refer to Jekeli (1999). This correspondence will focus solely on anomalous refraction and demonstrate that it represents a major obstacle for measuring ±0.01″-accurate (Φ,Λ) over a few hours on one night. For more general descriptions of astrogeodetic methods, refer to Mueller (1969) and Torge (2001).

DEFINITION AND ORIGINS OF ANOMALOUS REFRACTION

Atmospheric refraction is a general term that denotes ray-bending effects of the atmosphere on the geometry of the path of electromagnetic waves, e.g., of star light. The term *astronomical refraction* often describes the ray-bending "when the observer (here the telescope) is inside Earth's atmosphere and the target (here a star) is outside" (after Thomas and Joseph 1996, see also Hirt et al. 2010a). Based on the assumption of a radially symmetric atmosphere (Teleki 1979) with the zenith as the point of isotropic symmetry, astronomical refraction is usually modelled as a function of zenith distance. For details, see, e.g., Torge (2001, p.165), Stone (1996) and Young (2006), amongst many other treatments.

The specific term *anomalous refraction* describes any constituents of astronomical refraction that deviate from a radially symmetric model. As such, anomalous refraction denotes those parts of "*refraction that varies from the smooth analytical models of refraction that are functions only of zenith distance*" (Stone et al. 1996, Pier et al. 2003). In radially symmetric atmosphere models, refraction is assumed to disappear at the observer's zenith. Any distortion of the radial symmetry results in anomalous refraction. Amplitudes of anomalous refraction can usually range from ~0.01″ to few ~0.1″ at zenith (e.g., Sugawa 1956, Ramsayer 1967, Hirt 2006, Taylor 2009) and these effects increase with zenith distance (Bretterbauer 1965, p.117, Löser 1957, p.34, Hughes 1979 p.24).

Anomalous refraction is a phenomenon that has been mentioned, discussed or analysed in the literature for over 150 years (e.g., van de Sande Bakhuyzen 1868, Schlesinger 1905, Schubart 1954, Sugawa 1956, Sugawa 1958, Löser 1957, Milovanović and Pannwitz 1972, Sugawa and Kikuchi 1979, Dimopoulos 1982, Hampl 1987, Hu 1991, Kovalevsky 1998, Nedfedjev and Nedfedjeva 2005, Taylor 2009). Scientists often relate anomalous refraction to horizontal temperature or pressure gradients occurring in the atmosphere at or above the observation site. Such gradients result in tilted atmospheric layers and, in turn, give rise to refraction effects that depart from that of a radially symmetric model (e.g., Ramsayer 1967).

Horizontal temperature gradients or tilted layers are associated with: regional weather patterns or passing weather fronts (e.g., Sugawa and Kikuchi 1979, Stone et al. 1996); the environment around the observation site (Teleki 1979), such as sloped terrain (Bretterbauer 1965); and so-called urban heat islands, where regional changes in surface temperature come into play (Hughes 1979, Currie 1979). Convective movement of atmospheric air-masses and/or atmospheric gravity waves are further sources responsible for anomalous refraction (Naito and Sugawa 1984, Webb 1984, Stone et al. 1996, Taylor 2009, Taylor et al. 2010).

SOME THEORETICAL AND EMPIRICAL STUDIES ON ANOMALOUS REFRACTION

Our current knowledge on anomalous refraction is primarily based on

(1) meteorological data analysis,

(2) spot-check astronomical observations and, more recently,

(3) continuously performed refraction experiments.

Next, the concept behind each group of anomalous refraction studies is explained, and the main findings summarised. Star catalogue errors can be considered to have negligible effect on the results of all cited works published within the last decade, as these works make use of highly accurate Tycho-2 star catalogues catalogue (Høg et al. 2000) or other precise catalogues based on the Hipparcos satellite astrometry mission (ESA 1997).

(1) In *meteorological data analysis*, temperature or pressure measurements are taken either at scattered ground stations or in terms of vertical profiles using radio-sondes. Horizontal temperature or pressure gradients between any two stations or profiles can be converted to tilt angles of atmospheric layers, and ray-tracing algorithms are used to compute the associated anomalous refraction effects. Based on radio-sonde data, Sugawa (1956) found season-dependent anomalous refraction amplitudes of about 0.01″, and derived amplitudes of ~0.04″ from ground meteorology. Bretterbauer (1965) used observed pressure gradients in mountainous terrain and found anomalous refraction effects of 0.03″ to 0.17″ at zenith (ibid, p.117). For the Northern Hemisphere, Sugawa and Kikuchi (1979) published maps of anomalous refraction effects with amplitudes of ~0.003″. Takagi and Goto (1979) analysed meteorological data and found unsymmetrical refraction around the zenith, with refraction differences of ~0.1″ between Sterneck star-pairs, and reported a seasonal variation of 0.01″. Based on ground-based temperature gradient measurements, Dittrich (1981, p.150) derived correction terms for anomalous refraction as large as 0.2″.

More recently, Guillaume (2011) presented a seminar on the use of ray-tracing algorithms along with 4D meteorological data sets (3D temperature and pressure fields as a function of time). The high-resolution meteorological data set COSMO-2 (http://www.cosmo-model.org/) provides meteorological quantities in terms of 60 atmospheric layers (from 30 m to 20,000 m) with 2.2 km horizontal and 1 hour temporal resolution). Over a test area in Switzerland, ray-tracing through the layers of the 4D-model yielded maximum anomalous refraction effects of few ~0.1″ at zenith, with an average RMS signal strength of a few 0.01″ (Guillaume 2011). Details on these investigations will be presented in an upcoming paper.

(2) *Repeated observations* of astronomical coordinates (Φ,Λ) over many different nights (with varying atmospheric conditions) are an important source to constrain the maximum average amplitudes of anomalous refraction. Such observational data is available from

astrolabes or photographic zenith tubes (PZTs), used in the 20th century for determining Earth orientation (e.g., Vondrák et al. 1995), or, more recently, from digital zenith cameras (e.g., Bürki et al. 2004, Hirt et al. 2010b).

Ramsayer (1967) analysed refraction anomalies in the Potsdam Astrolabe data and found maximum observation errors of 0.3″ and a mean influence of refraction anomalies of 0.06″ (ibid, p. 265). Based on PZTs operated at Washington and Florida over many years, McCarthy (1979) reported internal errors of about 0.03″ and an accuracy estimate of 0.08″-0.09″ for single PZT measurements. McCarthy's values suggest that average amplitudes of anomalous refraction were no larger than 0.08″-0.09″ at these two observation sites. Nakajima (1979) analysed observational errors of the Tokyo PZT and reported accuracies of 0.04″ for 5-day means, and 0.03″ for monthly means, indicating some mitigation of refraction effects through forming averages over several days.

Hirt and Seeber (2008) used a digital zenith camera (a zenith telescope with 20 cm aperture, equipped a charge-coupled device (CCD) sensor for digital imaging) for repeated (Φ,Λ) and vertical deflection observations at a control site in Germany during ~100 nights over a 3.5-year period (2003-2006). Based on one-hour of star observations per night, precision of ~0.05″ was obtained, and it was found that small positive correlations between subsequent star observations prevented any further increase in precision, e.g., through additional observations during the same night. Hirt and Seeber (2008) concluded that "*anomalous refraction limits the attainable accuracy of vertical deflections observed* [with digital zenith cameras] *over one night to the level of* 0.04-0.05″". This value is much larger than that claimed by BAL03.

(3) More recently, astronomical telescopes with CCDs have been used for *continuous refraction measurements*, providing insight into the fluctuation of anomalous refraction with time. The basic idea is to compare high-resolution time-series (i.e., sequences of single measurements) of (Φ,Λ)-values or directions to stars against some (long-term) mean values formed from many observations. The mean values are assumed to be largely free of anomalous refraction, and residual differences between single measurements show how the atmosphere behaved above the telescope at a particular epoch of time (Stone et al. 1996,

p.1736). Stone et al. (1996), Hirt (2006) and Taylor (2009) excluded instrumental effects as main cause for the variations exhibited in their time series, as summarised in the following.

Stone et al. (1996) published probably the first time-series of continuous refraction measurements with a 20-cm CCD transit telescope. They found amplitudes of 0.1-0.2″ at time-scales of 3-40 min for observations at 45° zenith distance (Ibid. Fig. 17) and believed anomalous refraction to be the cause. Stone et al. (1996) determined anomalous refraction for other zenith distances and published an average effect ("atmospheric error") of ~0.09″ at zenith (Ibid. Table 7), which, however, can be reduced through some averaging strategy (Stone et al. 1996, p. 1737). Hirt (2006) used a digital zenith camera for monitoring of anomalous refraction over a total of 70 hours and found wave- and bump-like variations of about 0.05-0.2″ over a few hours, and indicated the presence of very low-frequency anomalous refraction effects of ~0.04″ over several days.

Probably the most comprehensive and detailed research record on anomalous refraction has been presented by Taylor (2009). Admittedly, this is after the publication of BAL03, but the effect of anomalous refraction was known before 2003. Over the years and more than 25 nights, Taylor (2009) studied the characteristics and fluctuations of anomalous refraction with a variety of CCD astrometry telescopes, from 10 inch to 2.5 m aperture. In all observations, Taylor found "*ubiquitous occurrence of anomalous refraction*", regardless of the telescope or location of observation (ibid, p. 181). The author emphasised there had been no nights or even fractions of nights where anomalous refraction was not present. Taylor (2009, p. 209) characterises anomalous refraction as "*quasiperiodic with periods ranging from minutes to hours and amplitudes from few* 0.1″ *on few minute time scales to* 0.5-1.5″ *on tens of minutes to hours timescales*".

More specifically, Taylor (2009, p. 209) finds high correlations of anomalous refraction across a telescope's 2.3° field of view [which corroborates a similar finding by Pier et al. (2003)], while noting a decrease in correlation with increasing spatial separation of imaged stars. Anomalous refraction turned out to be uncorrelated between pairs of telescopes used for simultaneous parallel observations at 2 to 300 metres separation (ibid p. 209). Based on analysing the parallel observations, Taylor (ibid p. 218) confines a main contributor to quasiperiodic oscillations of anomalous refraction to the lowest layers of the atmosphere (say ~100 m order), with spatial scales of correlation of less than 2 metres.

Taylor's results suggest that quasi-period anomalous refraction oscillations at time scales of minutes to hours, as also shown by Stone et al. (1996) and Hirt (2006), are mainly a local phenomenon that is attributable to air-mass convection in the lowest layers of the atmosphere above the observation site. Opposed to this, it is reasonable to associate long-period anomalous refraction constituents at time scales of ~days or ~months with more static phenomena such as regional weather patterns, heat island effects (near urban areas), or the topography around the observation site (terrain inclinations).

Though the above studies provide some insight into the characteristics of anomalous refraction, there is inarguably need for follow-up research aiming at understanding the complex nature of anomalous refraction. Further studies on the characteristics of anomalous refraction might be expected in the context of new CCD zenith telescopes (Ron et al. 2007). Nevertheless, all the above-cited studies do unanimously show that the effects of anomalous refraction render the ±0.01″ accuracy estimate of BAL03 to be unrealistic.

MITIGATION OF ANOMALOUS REFRACTION

Anomalous refraction is problematic for any accurate astronomical measurement of (Φ,Λ) because the effect cannot be eliminated in-situ. It was already noted by B. Guinot in 1971 (loc. cit. Teleki and Sevarlić 1972, p. 149) that anomalous refraction gives rise to a shift of the zenith, and thus to a common translation of all measured directions to stars, so cannot be cancelled out by two-face field measurements. This is because anomalous refraction causes astronomical observations to be correlated, at time scales ranging from ~minutes to ~months (see previous section).

From the above literature review, anomalous refraction can be mitigated to some extent by forming averages over some period of time (e.g., Nakajima 1979, p.775, Stone et al. 1996 p.1736, Hirt and Seeber 2008, Fig 8). Though reduction of anomalous refraction effects is possible, there is evidence that averaging is not capable of fully eliminating anomalous refraction effects, neither in the course of a single night nor over several nights (see Sugawa and Kikuchi 1979, Hughes 1979; Currie 1979, Hirt 2006 and Hirt and Seeber 2008). For instance, the topography of the observation site (Bretterbauer 1967, Stone et al. 2006) or prevailing regional weather patterns (Sugawa and Kikuchi 1979) give rise to temporal and spatial correlations in anomalous refraction. As another practical example, observation sites near land-water transitions might be prone to horizontal temperature gradients, and, thus, could give rise to anomalous refraction effects.

From a methodological point of view, corrections for anomalous refraction could be computed by evaluating refraction integrals, "*if the meteorological conditions were known along the line of sight at all times*" (Stone et al. 1996, p. 1736). "*This information could be obtained from Doppler radar, lidar measurements and from radiosondes, but is generally not available at most observation sites*" (ibid). Also, high-resolution gridded meteorological 4D-data sets may prove suitable to correct for anomalous refraction to some extent, however, this approach is still in its infancy and the effectiveness and limitations of this strategy is not yet explored fully (Guillaume 2011). As such, anomalous atmospheric refraction currently prevents reaching the ±0.01″ level of accuracy claimed by BAL03.

CONCLUDING REMARKS

"Anomalous refraction is ubiquitous" (Taylor 2009, p. 210): every optical telescope is constantly subject to anomalous refraction, regardless whether it is applied for astronomical or astrogeodetic tasks. A cursory literature review of pre- and post-2003 anomalous refraction studies suggests that amplitudes at the ~0.1″ level have to be expected. Even averaging repeated astrogeodetic observations cannot fully mitigate the effect of anomalous refraction because it is correlated in space and time. Thus, the current knowledge on anomalous refraction provides evidence that astronomical coordinates (Φ,Λ) cannot be routinely measured at the 0.01″-accuracy level within few hours of observation time on one night, as was suggested by BAL03. Of course, this objection holds for other astrometric and astrogeodetic observations.

POSTSCRIPT

Some references, particularly the historical works, cited herein are in German. These have been included for the sake of completeness. I also admit that some works cited herein have been published after 2003. Nonetheless, a large number of studies on anomalous refraction are in English and published before or well before 2003. Specifically, the proceedings from the 1979 Symposium of the International Astronomical Union on refractional influences in astrometry and geodesy are a rich source of information on this topic.

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REFERENCES

1. Balodimos, D.D., Korakitis, R., Lambrou, E. and Pantazis, G. (2003) Fast and accurate determination of astronomical coordinates Φ, Λ and azimuth, using a total station and GPS receiver. *Survey Review* 37 (290): 269-275.
2. Bretterbauer, K., 1965. Über mögliche Refraktionsanomalien infolge von Schichtenneigungen. *Österreichische Zeitschrift für Vermessungswesen*, 53(4): 113-119.
3. Bürki, B., Müller, A. and Kahle, H.-G., 2004. DIADEM: The New Digital Astronomical Deflection Measuring System for High-precision Measurements of Deflections of the Vertical at ETH Zurich. Electronic Proc. IAG GGSM2004 Meeting in Porto, Portugal. Published also in: CHGeoid 2003, Report 03-33 A (ed. U. Marti et al.), Bundesamt für Landestopographie (swisstopo), Wabern, Switzerland.
4. Currie, D.G., 1979. Two color refractometry, precision stellar catalogues, and the role of anomalous refraction. *IAU Symposium Refractional Influences in Astrometry and Geodesy* (ed. E. Tengström and G. Teleki): 131-155.
5. Dittrich, J. 1981. Relationen zwischen Störungen des lokalen Temperaturfeldes und den geodätisch-astronomischen Beobachtungsresultaten am Astrolab DANJON. *Astronomische Nachrichten* 302(3), 145-151.
6. Dimopoulos, T., 1982. Untersuchungen über die Genauigkeit der Ermittlung der astronomischen Refraktion. *Dissertation*, Fakultät Bauingenieur- und Vermessungswesen der Universität Stuttgart.
7. European Space Agency (ESA), 1997. The Hipparcos and Tycho catalogues. ESA SP-1200, European Space Agency.

8. Guillaume, S., 2011. Die Bedeutung des Schwerefeldes beim zukünftigen Linearbeschleuniger CLIC, Presented at Astronomisches Seminar, 11.04.2011, Astronomisches Institut, Universität Bern, Switzerland.

9. Hampl, J. 1987. Local refraction anomalies in the method of equal altitudes. Bull. Astron. Inst. Czechosl., 38, 131-135.

10. Hirt, C., 2006. Monitoring and Analysis of Anomalous Refraction Using a Digital Zenith Camera System. *Astronomy and Astrophysics*, 459(1): 283-290. DOI: 10.1051/0004-6361:20065485.

11. Hirt, C. and Seeber, G., 2008. Accuracy Analysis of vertical deflection data observed with the Hannover Digital Zenith Camera System TZK2-D. *Journal of Geodesy,* 82(6): 347-356. DOI: 10.1007/s00190-007-0184-7.

12. Hirt C., Guillaume, S., Wisbar, A., Bürki, B. and Sternberg, H., 2010a. Monitoring of the refraction coefficient of the lower atmosphere using a controlled set-up of simultaneous reciprocal vertical angle measurements. *Journal of Geophysical Research* 115, D21102, doi:10.1029/2010JD014067.

13. Hirt, C., Bürki, B., Somieski, A. and Seeber, G., 2010b. Modern Determination of vertical deflections using digital zenith cameras. *Journal Surveying Engineering,* 136(1), Feb 2010, 1-12. DOI: 10.1061/_ASCE_SU.1943-5428.0000009.

14. Høg, E., Fabricius, C., Makarov, V. V., Urban, S., Corbin, T., Wycoff, G., Bastian, U., Schwekendiek, P. and Wicenec, A. 2000. The Tycho-2 Catalogue of the 2.5 Million Brightest Stars. *Astronomy and Astrophysics* 355: L27-L30.

15. Hu, N., 1991. Ways to improve observational accuracy obtained by ground-based optical astrometric instruments. *Astrophysics and Space Science,* 177(1-2): 235-243.

16. Hughes, J.A., 1979. Environmental systematic and astronomical refraction. *IAU Symposium Refractional Influences in Astrometry and Geodesy* (ed. E. Tengström and G. Teleki): 13-25.

17. Jekeli, C., 1999. An analysis of vertical deflections derived from high degree spherical harmonic models. *Journal of Geodesy*, 73(1): 10–22, doi:10.1007/s001900050213.

18. Kovalevsky, J., 1998. Environmental disturbances of astronomical observations. *Astronomical Society of the Pacific Conference Series* (ed. Isobe S, Hirayama T.) 139: 89–96.

19. Löser, H.-G. 1957. Untersuchungen zur praktischen Berechnung von Refraktionsanomalien für die Zwecke der Orientierung nach Sonnenhöhen, Deutsche Geodätische Kommission B36, Frankfurt am Main.

20. McCarthy, D.D. 1979. Some advantages and disadvantages of a photographic zenith tube. In: IAU Symposium Time and the Earth's rotation (Eds D.D McCarty and J.D. Pilkington), San Fernando, 1978, No 82, pp 65-66.

21. Milovanović, V. S. and Pannwitz, H., 1972. On the night errors in astronomical determinations. *Bulletin Géodésique*, 46(2): 185-193.

22. Mueller I.I., 1969. Spherical and Practical Astronomy as Applied to Geodesy, Frederick Ungar Publishing, New York.

23. Naito, I. and Sugawa, C., 1984. Atmospheric refraction effects in time and latitude observations using classical techniques. In: *Geodetic Refraction* (ed. F.K. Brunner), Springer, Berlin, Heidelberg, pp 181-188.

24. Nakajima, K., 1979. Analysis of the Observational Errors of the Photographic Zenith Tube at the Tokyo Astronomical Observatory. *Publications of the Astronomical Society of Japan*, 31: 775-799.

25. Nedfedjev, Y.A. and Nedfedjeva, A.I. 2005. Determinations of refraction anomalies by global inclinations of airstratas of identical density. *Astronomische Nachrichten* 326, 773-776.

26. Pier, J.R., Munn, J.A., Hindsley, R.B., Hennessy, G.S., Kent, S.M., Lupton, R.H. and Ivezić, Ž., 2003. Astrometric Calibration of the Sloan Digital Sky Survey. *The Astronomical Journal*, 125(3): 1559–1579.

27. Ramsayer, K., 1967. Investigation on Errors in the Determination of Astronomical Refraction. Proceed. Intern. Symp. Figure of the Earth and Refraction, Wien. *Österreichische Zeitschrift für Vermessungswesen*, Sonderheft 25: 260-269.

28. Ron, C., Stefka, V. and Vondrák, J., 2007 The new CCD Zenith Tube. In: A Giant Step: from Milli- to Micro-arcsecond Astrometry Proceedings IAU Symposium No. 248 (Eds W. J. Jin, I. Platais & M. A. C. Perryman), pp 120-121.

29. Schlesinger, F. 1905. On systematic errors in determining variations latitude. Astronomical Journal, 24(574), 183-186.

30. Schubart, J., 1954. Refraktion und mittlerer täglicher Temperaturgang. *Astronomische Nachrichten* 281, 255-256.

31. Stone, R.C. 1996. An accurate method for computing atmospheric refraction. *Publications of the Astronomical Society of the Pacific* 108, 1051-1058.

32. Stone, R.C., Monet, D.G., Monet, A.K.B., Walker, R.L., Ables, H.D., Bird, A.R. and Harris, F.H. 1996. The Flagstaff Astrometric Scanning Transit Telescope (FASTT) and Star Positions Determined in the Extragalactic Reference Frame. Astronomical Journal, 111(4), 1721-1742.

33. Sugawa, C., 1956. On the Relation of the Anomalous Refraction on the Latitude Observations. *Publications of the Astronomical Society of Japan* 8(1): 27-39.

34. Sugawa, C., 1958. On the relation between the wind effect and the anomalous refraction in the latitude observations. *Publications of the Astronomical Society of Japan*, 10(2), 79-98.

35. Sugawa, C. and Kikuchi, N., 1979. On the Characteristics of Astronomical Refraction in the Northern Hemisphere. *IAU Symposium Refractional Influences in Astrometry and Geodesy* (ed. E. Tengström and G. Teleki): 103-117.

36. Takagi, S. and Goto, Y. 1979. Astronomical refraction at the Mizusawa latitude observatory. *IAU Symposium Refractional Influences in Astrometry and Geodesy* (ed. E. Tengström and G. Teleki): 119-124.

37. Taylor, S., 2009. On the Sources of Astrometric Anomalous Refraction. *Dissertation,* The University of New Mexico, Albuquerque, New Mexico.

38. Taylor, S., McGraw, J., Zimmer, P. and Pier, J., 2010. On the Sources of Astrometric Anomalous Refraction. American Astronomical Society, AAS Meeting #215, #387.05; Bulletin of the American Astronomical Society, Vol. 42, p.603

39. Teleki, G. and Ševarlić, B. 1972. On the determination of anomalous refraction out of astrometrical measurements in the zenith zone. IAU Symposium Rotation of the Earth (Eds P. Melchior and S. Yumi), pp 147-149.

40. Teleki, G. 1979. Research into astronomical refraction – today and tomorrow (a survey paper) *IAU Symposium Refractional Influences in Astrometry and Geodesy* (ed. E. Tengström and G. Teleki): 1-10.

41. Thomas, M.E., and Joseph, R.I., 1996. Astronomical Refraction. *Johns Hopkins APL Technical Digest*, 17(3), 279 - 284. The Johns Hopkins University.

42. Torge, W., 2001. Geodesy, Third edition. W. de Gruyter, Berlin, New York.

43. van de Sande Bakhuyzen, H.G., 1868. Ueber den Einfluss der Strahlenbrechung im Beobachtungssaale auf die mit dem Meridiankreise bestimmten Declinationen. *Astronomische Nachrichten* No 1720-1721, pp 241-260.

44. Vondrák J., Ron C., Pesek I. and Cepek A. 1995. New global solution of Earth orientation parameters from optical astrometry in 1900-1990, *Astronomy and Astrophysics* 297, 899-906.

45. Webb, E.K. (1984), Temperature and Humidity Structure in the Lower Atmosphere. In *Geodetic Refraction* (ed. F.K. Brunner), Springer, Berlin, Heidelberg, pp 85-132.

46. Young, A.T., 2006. Understanding astronomical refraction. *The Observatory*, 126, 82 - 115, URL: http://www.ulo.ucl.ac.uk/obsmag/