# THE STUDY OF ASTRONOMICAL REFRACTION IN TIME

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*Abstract*. From antiquity till now astronomers have been concerned with the modification of the direction from which the celestial bodies are observed as against their geometric direction. Thus, tables, principles, theorems, calculation methods, atmosphere models have been issued, which have been perfected in time. This paper presents this evolution briefly.

*Key words*: history of astronomy – astronomical refraction.

Astronomical refraction denotes the modification of the direction from which the heavenly bodies are observed as against their actual or geometrical direction, caused by the curvature of the light ray through the terrestrial atmosphere.

For over two thousand years astronomers have observed that the heavenly bodies seem to be placed a little more above the horizon than they really are. This phenomenon was attributed to the refraction through the Earth's atmosphere but it was understood in detail only a couple of hundred years ago. The phenomenon of refraction was described for the first time by Cleomedes de Mundo, at the beginning of our era, in his work *Cleomedes de Motu Circulari Corporum Caelestium* [63]. In the same work he rewrote a tabel of refraction, which means that the phenomenon had been known before. Cleomedes believed that water is the essential element in the curvature of the light ray through the terrestrial atmosphere. The phenomenon is described by Claudius Ptolemy in his work *Optica* [39] in similar terms. Ptolemy implies that refraction appears only at the horizon, while between the pole and zenith there is no difference, or only a negligible one, between its apparent and the actual positions.

At the same time with the determination of the refraction laws obtained experimentally, at the beginning of the 17th century the refraction phenomenon was approached by some of the greatest mathematicians of the world. Outstanding figures who approached these laws are T. Harriot, Snell, Descartes, Newton.

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The first tables of solar and stellar refraction, obtained on the basis of observations, were drawn up by Tycho Brahe and were published in 1602. J.Kepler brought specifications concerning the values of refraction in the neighbourhood of the horizon on the basis of T. Brahe's tables in 1604 and published other tables , more exact, in 1627. The geometric description of the refraction phenomenon and the correction of some errors in Kepler's tables was done by J.D. Cassini in 1692. J. Cassini perfected his father's theory, his geometrical model becoming classical. He also did many observations for the refraction at the horizon, published in 1714.

In 1715 Brook Taylor obtained a differential equation of refraction. He proposed the determination of refraction through series developments, which remained valid even today in the calculation of refraction for zenithal distances under 81°.

The work which inspired Oriani's theorem, which refers to the fact that the atmosphere density law does not influence refraction for zenithal distances under 70°, is *Mathematical Dissertation on a Variety of Physical and Analytical Subjects*, 1743, written by T. Simpson, B. Oriani, in his work *De refractionibus astronomicis*, 1787, stated the refraction phenomenon, deduced the refraction invariant and established the theorem bearing his name. About the integral of the refraction developed in series, from which the first two terms are retained, for zenithal distances under 70°, Oriani wrote : „ This expression does not depend on any hypotesis about any law of atmosphere or air density when the distance varies up against on the Earth's surface".

In 1799, Cr. Kramp, in the monography *Analyse des Réfractions Astronomiques et Terrestres* invented the gamma function, useful in the evaluation of refraction integral in the neighbourhood of the horizon. Additionally, Kramp updated the terminology specific to refraction. The gamma function was resumed almost 85 years later by Radau who notated it again and drew up tables with its values, making it thus easily applicable.

The reference theory of refraction is presented in *Traité de mécanique céleste*, 1805, elaborated by P.S, Laplace.

Beginning with 1821 J. Ivory published a series of works on the topic of refraction. He took into consideration the Cassini model, Laplace formula and developed the polytropic model. His theory was criticized by T. Young, who sustained the idea of the series development of the refraction integral and the extrapolation at the horizon. Furthermore, in 1822, T. Young considered that the atmosphere structure can be deduced from the refraction data, an idea sustained even today by physicists, given the increase of the refraction tables precision. After the publication of Emden's work, Gaskugeln [13], it became possible to study refraction by means of the polytropic atmospheric models [ 14, 17, 1]. Thus astronomical refraction for any zenithal distance can be calculated.

J.B. Biot, in *Sur les réfractions astronomiques*, 1836, gives a theorem about refraction at the horizon. Biot has the merit of having analyzed in detail Newton's refraction tables and to have approached rigorously atmosferic refraction.

Beginning with the second half of the 19th century were devloped various deduction methods of refraction invariant, refraction integral, different series developments of the latter one or its evaluation through numerical integration. This is also due to the fact that the new technology allowed the obtainance of atmospheric models ever closer to the actual atmosphere.

The refraction issue was approached in other ways, as well. Thus, Harzer [20] is the first astronomer who deduced the formulas for the calculation of refraction exclusively by means of the available meteorological observations, made both at the surface of the Earth, as well as at various heights. The number of these observations increased very much, as well as their precision.

Another method of evaluating refraction, very common at present, is the method of numerical integration. When it comes to the neighbourhood of the horizon, the knowledge of the air density depending on height is of vital importance. F. Link approached this method in 1934 [27], 1937 [28] and then in 1958 [29], calculating the tables of refraction values for average latitudes.

In our country, in 1899, N. Coculescu in *Teoria refracţiei astronomice* [7] obtained the integral of astronomical refraction using Fermat's principle ( the luminous trajectory reduces to the integral of refraction index to the minimum as against the arch element) and also the fact that a curve with the characteristics of the luminous trajectory is the equilibrium position of a tension wire. Thus, Coculescu demonstrated that the trajectory of the light ray is plane and obtained the invariant of refraction initially deduced by Laplace.

In 1935, T. Vescan [55] used the Cassini model and calculated the refraction integral by replacing the distance from the model center to a point of the luminous trajectory with the vector ray of a parabola with the pole in the observation point. Thus, he obtained a refraction formula depending on the atmosphere height significant for refraction, the average radius of the Earth and the parabola parameter which approximated the luminous trajectory . We mention at the same time that in 1957 Gh.Chis and St. Radu drew up tables of differential refraction [6].

After the setting up of the Committee for Space Researches, COSPAR (Committee on Space Research), the scientists' collaboration concerning the research of the cosmic space underwent a great development, the problems of atmosphere study being approached in a new way. Thus, N.I. Dinulescu contributed to the study of astronomical refraction on the basis of the new atmosphere models, by means of numerical integration and computers programming, becoming thus integrated into the new current from the second half of the 20th century.

Similarly, in 1973, looking for a mathematical model closer to reality than the concentric spherical model, I. Mihaila [ 33] established the refraction integral for the ellipsoidal model of atmosphere, namely when the refracted ray is situated in the meridian plane of the observation place.

Astronomical refraction is a phenomen very much studied throughout time . At present researchers are trying to obtain refraction tables as precise as possible . This is required in the first place by a precise drawing up of stellar catalogues. It is necessary that the instrumental errors in the observed positions of the stars be corrected , then the latter ones to be reduced taking into account astronomical refraction and diurnal abberation, thus obtaining their apparent positions.

Thus, as stated at IAU Symposium 89 of 1978 [53], the first one dedicated to the refraction issue , the results of ground based astrometry can be improved in the sense of increasing their precision through a better knowledge of refraction influence at the same time with the existence of ever more perfected instruments. As Teleki stated at this symposium, to give exact values of refraction is even more difficult than to build high class astronomical instruments.

This fact speaks for itself about the importane of studying refraction in the future for the astrometric measurements on the ground. Teleki separates optical refraction, also called astronomical refraction, decomposing into pure refraction and irregular refraction. Pure refraction is defined as a component of astronomical refarction in the vertical plane of the observation place, if atmosphere is a medium with the characteristics of an ideal gas in hydrostatic equilibrium, in a newtonian gravitational plane and with a spherical concentric distribution of density. As far as irregular refraction is concerned, it is defined as the difference between the real and the pure refraction. Pure refraction is calculated by means of the classical integral of refraction, used to obtain variation tables of refraction.

The problem of refraction in the case of non-spherical atmosphere has known new approches in the last decades, at the same time with the increase of the precision necessary for the astrometric determinations [22], as well as in connection with the motion of the Earth's artificial satellites. Worth mentioning are, for instance, the researches made by Kolchinskii ( who shows that the Oriani-Laplace theorem can be applied up to the zenithal distance of 70°) [] and Nefed'eva ( who deduces the wave lengths from the refraction constant applied to different tables)[].

We also mention that in a study dedicated to refraction in the neighbourhood of the horizon. A.T.Young [63] underlines the importance of approching refraction calculation in this case through numeric integration, without resorting to series developments. Elsewhere, Guseva [19] proposes the calculation of refraction integral in the neighbourhood of the horizon through numerical integration form a conveniently chosen height. She calculates the integral analytically, from the ground to that height, introducing the variation of the refraction index depending on the distance from the center of the atmosphere model to the air stratum taken into consideration.

The integral of astronomical refraction is non-convergent for a zenithal distance of 90. Studies were made on the factors which influence refraction at the horizon. We mention the work of S.Y van der Werf [] and A.T. Young []. We have proposed a method of refraction determination, which calculates refraction at iteratively, on the basis of an atmosphere model, through a direct application of refraction laws. The advange of this method consists in the fact that it can be applied also to the zenithal distance of 90 [32].

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