RESEARCH INTO ASTRONOMICAL REFRACTION - TODAY AND TOMORROW
(A Survey Paper)

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SUMMARY: Proceeding from the present-day and future needs of astrometry, current researches into astronomical refraction as well as its prospective development are analysed. Particular attention is dedicated to the constructing of new refraction tables, determination of the refractional influences by way of experiments, site selection of the observing stations and to the preventive measures to be taken at them. Need and usefullness are emphasized of the cooperation of experts specialized in astronomical, terrestrial, photogrammetric, radio and other kinds of refractional influences.

1. INTRODUCTION

Members of the Working Group on Astronomical Refraction of the IAU Commission 8 have laid down in a collection of papers (Teleki, 1974a) their views on the present state and future of astronomical refraction investigations. The following conclusion is found in the introductory article (Teleki, 1974b) of this paper collection: "Refractional investigations are needed especially at this moment when we have new astrometrical methods, fundamentally different from the classical ones, and we must compare the old and the new data. At this comparison the possible refractional influences must be known with higher accuracy than nowadays, because there are some unconfirmed beliefs and prejudices related to that". This statement remains in force at present as well. If any change has taken place in the last 4-5 years, it consisted in the tendencies in astrometry becoming prominent toward adopting new methods and instruments, their being intensively worked upon, but the impression is not to remove that the researches into astronomical refraction do not follow this trend.

Besides classical instruments already in existence, in the astrometry of the future new ground-based optical instruments, artificial satellites with astrometric missions, radio astrometry (very-long-baseline interferometry) as well as laser techniques must be reckoned with. To illustrate what new types of instruments are capable of offering let

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the example of "Space Astrometry Hipparcos" satellite (ESA, 1978) be pointed out: an accuracy of 0″.0015 is expected in the position determination of stars brighter than 11th magnitude, that of parallax up to 0″.002 and annual proper motion to 0″.002. Classical ground-based instruments, whose internal errors are characterised by the amounts 0″.2 - 0″.4, whereas external errors might even be larger, cannot compete with the new techniques. To achieve this, new ground-based instruments should be created and placed into favourable astro-climatic conditions. Høg (1975) puts the estimate of the productivity of the present-day and future meridian circles as follows: if the annual weight of the present-day meridian circles is taken as unit, the weight of the photo-electrical circles amounts to 15, that of horizontal circles to 40, and, if the latter are placed in exceptionally favourable conditions, a weight up to 800 is attainable. But even if the latter came true, great though its significance might be, it is nevertheless reasonable to expect these results to be at least one order of magnitude inferior to those obtainable by Hipparcos Satellite. Still this ground-based technique might be a complementary one to the new techniques. Failing this, the reason of existence of these instruments and methods is lost - as will soon be the case of the classical methods of pursuing the elements of the Earth's rotation.

It is self-evident that in speaking about astro-climatically favourable location, total effect of the atmosphere on the astrometric results is meant (Teleki, 1978). A location is favourable provided it renders possible a reduction, elimination or reliable calculation of individual effects. By appropriate protection of the instruments it becomes to considerably reduce, even to eliminate atmospheric effects on them and on the equipment attached to them. Thus, refractional influences constitute the basic problem. They can be reduced or, given favourable conditions, even calculated, which is otherwise impossible at locations with complex atmospheric structure (on this question see 4.1.).

What about the present-day accuracy of the determination of refractional influences? The accuracy of the calculated refraction value within the optical range is of the order of a few hundreths of an arc second, the uncertainty increasing with zenith distances (Teleki, 1974b).
A somewhat better position prevails in the calculation of the refraction of radio-waves, but it is even there not satisfactory (Bean, Teleki, 1974; Altenhoff, 1974). The calculation of the influence of the local atmosphere constitutes central problem in both cases.

It is therefore evident that a better knowledge of the refractional influences, in parallel with the existence of more perfect instruments, provides one of the keys to the increase in the accuracy of the ground-based astrometric results. To give accurate values of refraction is as difficult a task, if not even more difficult, than the construction of a new high quality astrometric instrument. This in itself speaks of the importance of the study of refraction for the future of the ground-based astrometric measurements.

In this review we are going to confine ourselves to the part of the optical refraction called astronomical refraction, decomposing it into pure and anomalous refraction (Teleki, 1974b). Pure refraction is defined as the component of the astronomical refraction in the vertical plane of the observer's place, assuming the atmosphere is a medium with characteristics of an ideal gas in hydrostatic equilibrium, in a Newtonian gravitational field and with spherically symmetric distribution of density. As for anomalous refraction, its definition is: the difference between the true and the pure refraction. Pure refraction is calculated by the classical integral of refraction, which serves for the forming of various refraction tables. One may therefore say that the anomalies are corrections to the tabulated refraction values.

2. PURE REFRACTION, REFRACTION TABLES

2.1. In solving classical integrals of refraction not only formulae, as simple as only possible, for the calculation of the influence are required, but the possibility is of prime importance of their application at greater zenith distances. Out of more recent expressions that of Saastamoinen (1974) is expedient up to 86^{o} zenith distance, while that of Garfinkel (1967) is applicable to all zenith distances from 0^{o} through 180^{o}. These are, to be sure, rather mathematical than physical and meteorological, possibilities of the refraction calculation. It is realistic to assume the refraction tables as being capable of securing 98% of the true value of that influence for the zenith distances up to 60^{o}–70^{o}. At zenith distances beyond this limit the deviations may be excessive (Kolchinskij, 1976), thus astrometric measurements, requiring high precision, are not to be made as far off zenith. This is confirmed by Vasilenko and Kharitonova (1977) who, by applying the method of statistical orthogonal expansion of refractive index, obtained more accurate values of the influences at greater zenith distances (80^{o}–88^{o}); it is estimated that the total calculated error amounts to about $3''.9$ (i.e. 0.3%).

2.2. In the current astronomical praxis most in use are Pulkovo Refraction Tables, Fourth Edition (1956). The investigations of Teleki (1967), Nefed'eva (1973) and others have revealed the deficiencies of these Tables, of which we are going to mention: inadequate value of the refraction constant and the correction for the air temperature.

It became clear that more up-to-date refraction tables were necessary. Two activities were therefore started: first, proceeding from her researches, Nefed'eva (1973)compiled new tables, and, second, the need was pointed out of the forming of international tables, to be standard in astrometry.

2.3. The constructing of the international tables of the kind indicated has been urged by the resolution of the IAU Commission 8 in 1973. As can be seen from detailed plan of their forming (Teleki, 1977), the goal set were tabulated values closer to reality. This means that instead of the refraction values obtained for some idealized conditions, such values are given as correspond closer to the real physical and meteorological circumstances.

Basic question is, doubtless, that of choosing the model of atmosphere most corresponding to reality. The work on this is going on, but early researches of Sugawa and Kikuchi (1974, 1975) already let us comprehend the importance and need of these analyses.

The tables are to be formed in such a way that the refractional influences may be calculated directly in terms of the refractive index in the surface air layer. The possibility is thereby presented to make use of data obtained by the refractometer.

In connection with the forming of these modern tables or of some others on the same lines, the question arises whether they are necessary at all at the present time. As an alternative, the calculation is suggested on the basis of aerological measurements, carried out simultaneously or approximately at the same time with the astrometric observations, the use of local refraction tables etc. In handling questions of this type the principle is to be followed: such method should be applied which under circumstances is capable of offering optimal results. It may be said that a need for accurate tables continues to be felt. One of the reasons is their being capable of providing the first frame of the refractional influences, indispensable for the comparison of the data obtained at various stations.

3. EXPERIMENTAL METHODS

Calculated values of refractional effects on the basis of tables - obtained for some averaged and idealized conditions - are long since insufficient to meet astrometric needs. Hence many efforts have been made to improve them. This is being performed either by determination of the anomalous refraction (as corrections to the tables), or by determination of the total refractional effect (indenpendent of tabular values) for a given place and time. This is usually made by way of experiments.

In seeking true values, emphasis is to be placed on the following: not only values of the anomalies or the total influences in the vertical plane are required (as in the case of pure refraction), but values of the horizontal components are necessary too. Thus, full space characteristics of the effects must be ascertained.

In view of this and by meteorological considerations we are led to infere that local effects are most difficult to know - those not contained in the tables (except effects of the average temperature, humidity and pressure), but essential for obtaining true values (Teleki, 1967; 1969; 1974c). To be more explicit here is an information:

by exploring the atmospheric turbulence by means of radio sondes up to 20 km altitude, Barletti et al. (1977) came to the conclusion that once the local turbulence (ground convection and orographic disturbances) is eliminated, all sites show the same average atmospheric properties.

It is therefore understandable that such methods are to be considered as most convenient which take into account just these local factors. Ideal methods, at the same time most difficult also, are those intended to determine the influences in their totality and not only parts of them.

3.1. The oldest method of determining refraction values is that based directly on the results of astrometric measurements. The first refraction tables owe their origin to this procedure. This method requires, quite clearly, a definite mathematical model of the refraction influences which makes possible the singling out of separate components. As a result of their analysis, Teleki and Shevarlich (1971) have stated the following factors, as impending the shaping of a satisfactory model: variable nature of meteorological elements, irregular formation of the air layers around the instruments, the variability of the instrumental characteristics (systematical and accidental) and errors in star coordinates. If these reasons stand - and they do stand - then it is practically impossible to devise an universal method for singling out of refractional influences from astrometric measurements. The authors came to the conclusion that a rigorous method must fulfil the following conditions: a) the shortest possible time for the measurement of the observational values required, b) the use of high quality instruments, whose characteristics and constants are practically unchangeable, c) the elimination of errors in star coordinates, and d) the analysis is to be made within narrow zones according to zenith distances. The meaning of these conditions is the suppression of the interpolation and extrapolation alike in time as in space. It is just upon these foundations that the authors proposed a method of the determination of anomalies in the circum-zenithal zone, which however has not as yet been employed (due in the first place to technical difficulties).

Unfortunately, the methods proposed do not, in their majority, comply with the above stated principles. By habit, universal methods are offered, implying the adopted models as being general: these methods are based on models, expressed, in the last instance, by tg z or $\sec^2 z$ (where z is the apparent zenith distance). In consequence, the nature of the values derived becomes very problematical. As an example take the determination of the so called constant of refraction from observations of one and the same star at upper and lower culminations (Teleki, 1977).

It may therefore stated that the methods intended at the singling out of refractional influence from astrometric measurements are without prospects in the future.

3.2. In view of what is presented in 3.1., attempts have been made and will be made to devise rigorous methods by which atmospheric parameters could be determined and on that basis refractional influences calculated. In brief, the procedure should consist not in singling out effects from astrometric results but should be quite indenpendent of them.

Aerological measurements have permitted a better knowledge of the free atmosphere, with all its variations in time and space. The calculations of the refractional influences directly from aerological measurements have already began. It was considered that in doing so instantaneous state of the local atmosphere has been fully accounted for. But this is only partially so. The main objection rests on the fact that these calculations are made on the basis of one sounding, as a matter of fact in the vertical direction, implying thereby the air layers to be spherically and the law of tg z to be valid. But it is evidently not true (Teleki, 1974c).

Aerological as well as analogous measurements by means of artificial satellites (Teleki, 1974d) yield useful informations about the upper atmosphere layers, but leave open the question of the exploration the atmosphere in the vicinity of the astrometric instruments. There, unfortunately no advance has been recorded. The determination of the direction and velocity of winds and temperature measurements on a single or several points were not sufficient to provide necessary elements for the calculation of the meteorological model of the local atmosphere.

What might be expected in the future? More rigorous methods should be applied in the research into the lower atmosphere - one of the methods is based on the acoustic sounding techniques (Bean, Teleki, 1974). However, as the lower atmosphere is a very turbulent and complex medium, one cannot expect this method to yield complete and precise information on the refractional influences in the near future. There is still a strong reason for the hope that the meteorology of boundary layer will develop in the years to come, which will stimulate research into refraction. New analysis may therefore be expected of the density field around the observational pavilion (Kakuta et al., 1974), of the influence of the urban heat islands (Hughes, 1974), various characteristics of the local atmosphere (Goto, 1978) and others.

3.3. In recent time much is worked in geodesy upon multiple-wavelength (dispersion) method for the elimination of the refractional influences - a survey of these investigations is given in Prilepin (1974). The basic principle (Joshi, Mueller, 1974) is described by the following: if several frequencies operating simultaneously to measure range between two points were assumed to follow the same straight line between end points (although there will be little deviation), then the only source of error in each of measurements is the retardation due to refraction of the atmosphere. The idea was put forward to apply this method in astrometry (Tengström, 1968). The method is not without its deficiencies and cannot simply be used even in geodesy, still less in astrometry. The striving of E.Tengström at the Geodetic Institute at the Uppsala University and of D. Currie at the University of Maryland

Physics Department to apply the dispersion method in astrometry therefore be acclaimed. The results may be expected to be interesting as such methods are just looked for by which determination or elimination of the total amount and not of part of refraction is possible.

3.4. The artificial satellites with astrometric missions can in the future render great services in providing information on the refractional influences. It will be possible to determine via these satellites stellar coordinates with high accuracy, accordingly it will be possible to eliminate the hindrance under c) in 3.1. Of particular usefulness for discerning instantaneous effects will be simultaneous observation from the satellite and with ground-based instruments. But this possibility may be reckoned with only by the end the next decade.

4. PREVENTION

The most promising "combating" the unsufficiently accurate refractional influences is prevention: the best possible location of the instrument, most adequate pavilion and observing method.

4.1. The majority of the astrometric instruments is unadequately located (proximity of cities and buildings; nonadequate pavilions; intricate air density field around the instruments; to many cloudy nights; unsteady image, etc.). Consequently the accuracy of the results of observations is considerably lowered. What prospects are offered by a convenient location can be seen from Høg's estimate (1975), referred to already in the Introduction. In any case the inference should run on the following lines: before deciding upon the location for an astrometric instrument, meteorologic exploration should carefully be carried out, while the station and the pavilion should be constructed in such a fashion as to secure the best possible stability and at the same time the density field as simple as possible (Teleki, 1974b). The instrument housing should be aired by ventilator.

These preventive measures should be taken not only on account of the refraction of the light ray but also in order to reduce the amount of the total atmospheric influence on the instrument and its accessories. The importance of the instrument protection is a fact sufficiently pointed out. Less emphasised but equally important is the protection of accessories. As a highly positive example we mention the introduction of vacuum meridian marks (Mitich, 1974; Mitich, Pakvor, 1977), by means of which the pursuing of the azimuth variations of the instrument is performed with an accuracy bordering to the theoretical one (mean error of a single setting on the meridian mark is $\pm 0\overset{s}{.}005$ while that of ordinary meridian mark is $\pm 0\overset{s}{.}013$ at best).

4.2. Much can be gained by the correct choice of observing methods of determining certain quantities (latitude, declination, etc.) enabling

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the reduction or even elimination of the refractional influences.

Differential methods - such as Talcott's method of latitude determination, astro-photographic methods of position determination, etc. - are capable of eliminating the better part of these influences, but not all, as anomalous refraction is usually left out, affecting to a considerable degree the final accuracy (Teleki, 1968).

It is difficult to devise such observing methods which would enable refractional influences to be completely eliminated. This is a consequence of the difficulties associated with the choice of a proper model through which this elimination would be possible. The same applies to the classical methods (see 3.1.) as well as to the more recent dispersion method (see 3.3.). Thus, the procedures suggested are to be looked upon rather critically. All to often we are confronted with some mathematical solution of the problem which is lacking sufficient physical and meteorological backing.

4.3. With the observing methods currently in use, where no possibility of eliminating refractional influences is given, care should be taken that observations are not made at too large zenith distances, certainly not beyond 60°-70°. This limitation is imposed alike to absolute as well as to differential methods of observations.

4.4. One should be careful in taking meteorological data on the surface layer, necessary for the computing of the pure refraction. By this we mean the measurement of these quantities at a given time (not the averaged ones), made with sufficiently precise equipment and always close to the object-glass of the instrument. These measurements should preferably be made by refractometers, which yield refractive indices by a whole order of magnitude more precise than those by the formulae (Teleki, 1974b; 1974c).

5. CONCLUSIONS

At the end, the following conclusions might be drawn:

5.1. Astrometry needs more accurately known refractional influences than we are nowadays able to offer;

5.2. Refraction tables, giving values for ideal and average conditions, must be brought closer to the reality;

5.3. Not even improved refraction tables are capable of meeting present-day needs, which necessitates special investigation of refractional effects at a given place and for a given time;

5.4. Preventive measures should be strictly observed; careful site selection, adequate pavilions, instruments, accessories and observing methods. Observations should not be made at zenith distances over

60^o–70^o, and meteorological data should cautiously be collected. Refraction, though a unique phenomenon, has hitherto been investigated piecemeal as astronomical, terrestrial, photogrammetric, radio or some other. A synthesis of these partial knowledges recommends itself as well as a continual cooperation of the experts in these fields. Astrometry would immensely benefit by such cooperation as more information would be acquired, in the first place that related to the surface air layers, which in other fields is considerable more widely investigated.

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