

Differential measurement of atmospheric refraction using a telescope with double fields of view

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Abstract For the sake of advancing theoretical research about atmospheric refraction, the atmospheric refraction observed at lower angles of elevation is still worth analyzing and exploring. In some engineering applications, objects with a larger zenith distance must sometimes be observed. Carrying out observational research on atmospheric refraction at lower angles of elevation has an important significance. However, it has been considered difficult to measure the atmospheric refraction at lower angles of elevation. A new idea for determining atmospheric refraction by utilizing differential measurement with double fields of view is proposed. Taking the observational principle used by the HIPPARCOS satellite as a reference, a prototype with double fields of view was developed. In August 2013, experimental observations were carried out and atmospheric refractions at lower angles of elevation were obtained by the prototype. The measured value of atmospheric refraction at a zenith distance of 78.8° was $240.23'' \pm 0.27''$, and the feasibility of differential measurement of atmospheric refraction with double fields of view was verified. Limitations of the prototype, such as inadequate ability to gather light, lack of accurate meteorological data recording, and a low level of automation in observation and data processing, are pointed out, which need to be improved in subsequent work.

Key words: astrometry — atmospheric effects — methods: observational

1 INTRODUCTION

Atmospheric refraction is the difference in the direction of light from a celestial body before the light enters the atmosphere and the direction when it reaches the observer. In comparison with other factors which affect the direction of light from a celestial body, atmospheric refraction is characterized by its uncertainty, mainly because atmospheric refraction at different locations can be different and, at the same location, atmospheric refractions in different directions are not exactly the same.

Especially at larger zenith distances, the influence of these two cases is more prominent. One important issue in ground-based astrometry is how to establish more reasonable atmospheric refraction models and how to improve the accuracy of correcting for atmospheric refraction.

With regular releases of high-precision star catalogs, the method of relative celestial positioning based on photography can effectively reduce the influence of atmospheric refraction. But in many areas, a high-precision correction for atmospheric refraction is still necessary. For example, in the process of creating a global pointing model for a telescope, the stars at lower angles of elevation must be observed because atmospheric refraction at larger zenith distances needs to be known precisely.

As another example, when tracking a target in low Earth orbit using the method of shaft positioning, or when tracking telemetry returned by a spacecraft from a ground station or a ship operating at sea, large zenith angles may be required. When carrying out a trajectory measurement in local ground-based experimental tests, the farther the target is away from the observer, the lower the angle of elevation becomes, and even a negative angle of elevation can appear. The correction error needed for atmospheric refraction has become one of the main errors arising from measurement in ground-based experimental tests (Wang et al. 2013; Zhou & Zhao 2012). The usual method of correcting atmospheric refraction is to adopt a general theoretical model (Zhao 2012; Zhang et al. 2013), but atmospheric refraction has local characteristics. In particular, at a large zenith distance, the actual value of atmospheric refraction may seriously deviate from the theoretical one. Therefore, how to obtain high-precision atmospheric refraction at a large zenith distance is one key to improving the accuracy of a global pointing model for a telescope, which can improve the observational accuracy and lengthen the observational arcs of the tracked target. In addition, in the field of space geodesy, atmospheric refraction delay is receiving increasing attention. A link should exist between atmospheric refraction and atmospheric refraction delay. Utilizing this kind of relation, some researchers proposed a method for transforming the atmospheric refraction observational model into an atmospheric refraction delay correction model, which is able to overcome the shortcomings of the adopted theoretical model and empirical model (Mao et al. 2006, 2007). This sort of application revitalizes observational research on atmospheric refraction.

The fundamental way of improving the correction accuracy of atmospheric refraction is to adopt an effective method to carry out actual measurements at an observing station, in combination with instantaneous meteorological data, that can be used to build a position-dependent observational model of atmospheric refraction. It has been considered difficult to measure the atmospheric refraction at lower angles of elevation. In 2008, we proposed a set of differential measurement methods for atmospheric refraction (Yu et al. 2009). The principle can be outlined as follows. A telescope with a larger field of view is employed to make a series of observations of stars around a target with different elevations and the derivatives of various orders of the atmospheric refraction function at different zenith distances are calculated according to the comparison between observational and theoretical arcs defined by the grouping of stars in each field of view, so the actual observed values of atmospheric refraction can finally be found via numerical integration.

In contrast to previous absolute measurement methods, such as the determination of local atmospheric refraction carried out by a Lower latitude Meridian Circle telescope (Mao et al. 2009). This method could minimize the effect of systematic errors, such as the local parameters and instrumental parameters. Several test observations have been done and they indicate that the idea of the determination of atmospheric refraction with the differential method is feasible, but the observational results also show that a measurement using a telescope with a single field of view would be affected by cumulative error, which will influence the final observed values of atmospheric refraction.

How to improve the observational accuracy is a key problem for the differential measurement of atmospheric refraction. After analysis and study, we proposed an idea of differential measurement of atmospheric refraction with a telescope with double fields of view, developed a prototype, and conducted experimental observations based on the prototype to investigate its feasibility.

In the present article, the principle of differential measurement of atmospheric refraction with double fields of view is introduced in Section 2. Information about the prototype is shown in Section 3. The experimental observation results are described in Section 4. Finally concluding remarks are given in Section 5.

2 FUNDAMENTAL PRINCIPLE OF DIFFERENTIAL MEASUREMENT OF ATMOSPHERIC REFRACTION WITH DOUBLE FIELDS OF VIEW

A telescope with double fields of view is employed to simultaneously observe two sky regions at different zenith distances. The atmospheric refraction at a larger zenith distance is calculated by comparing the actual arc length of the centers of the two fields of view (as determined by the measurement instrument itself) with the theoretical one (as calculated by apparent positions of observed stars). The specific calculation can be described as follows:

Let z_i be the true zenith distance of a star and z'_i be the observed zenith distance, then

$$\Delta z_i = z_i - z'_i \quad (1)$$

is the atmospheric refraction. For the simultaneous observations of the two fields of view at different zenith distances of the same azimuth, there is

$$L_0 = (z_2 - \Delta z_2) - (z_1 - \Delta z_1) = (z_2 - z_1) - (\Delta z_2 - \Delta z_1), \quad (2)$$

where z_1 , Δz_1 and z_2 , Δz_2 represent the corresponding variables of small and large zenith distances respectively; L_0 is determined by the measurement instrument itself, which represents the actual angular distance between the two fields of view; $z_2 - z_1$ is the difference in the true zenith distances between the two fields of view, which can be calculated from positions of stars in catalogs, observation times and the local constants related to the observing site; and Δz_1 is the atmospheric refraction at a small zenith distance. This can be obtained by the theoretical model which is sufficiently accurate under the condition of smaller zenith distance. So, the atmospheric refraction Δz_2 at a large zenith distance can be obtained according to Equation (2), which is

$$\Delta z_2 = (z_2 - z_1) - L_0 + \Delta z_1. \quad (3)$$

But in fact, it is impossible to observe the two points at exactly the same azimuth because of the pointing error of the telescope, i.e. the centers of the two fields of view cannot be on the same vertical circle. There will be some difference in azimuth between the two sky regions, so the calculation of a spherical triangle needs to be carried out to get the atmospheric refraction at a large zenith distance. As shown in Figure 2, let Z be the zenith, and σ_0 and σ_1 be the observed positions of the centers of the two fields of view. Their corresponding horizon coordinates are then (A_0, h_0) and (A_1, h_1) , and

$$\sigma_0 \sigma_1 = L_0. \quad (4)$$

Their azimuths and true zenith distances can be calculated according to the positions of stars in a catalog, observation time and local constants related to the observing site. Under normal circumstances, atmospheric refraction does not affect the azimuth of a celestial body, so there is

$$\angle \sigma_0 Z \sigma_1 = \Delta A = A_0 - A_1, \quad (5)$$

$Z \sigma_0$ can be calculated by the theoretical model of atmospheric refraction. In the spherical triangle defined by $\angle Z \sigma_0 \sigma_1$, the sine formula of a spherical triangle is expressed as

$$\frac{\sin Z \sigma_0}{\sin \angle Z \sigma_1 \sigma_0} = \frac{\sin \sigma_0 \sigma_1}{\sin \Delta A} \quad (6)$$

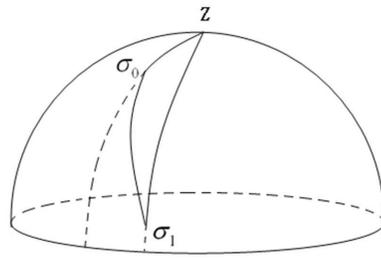


Fig. 1 Schematic drawing of the celestial sphere in an observation with double fields of view.

which can be used to get $\angle Z\sigma_1\sigma_0$ at first, and then the cosine formula of a spherical triangle is expressed as

$$\cos \sigma_0\sigma_1 = \cos Z\sigma_0 \cos Z\sigma_1 + \sin Z\sigma_0 \sin Z\sigma_1 \cos \Delta A \quad (7)$$

and is combined with the five-element formula of a spherical triangle expressed as

$$\sin Z\sigma_0 \cos \Delta A = \cos \sigma_0\sigma_1 \sin Z\sigma_1 - \sin \sigma_0\sigma_1 \cos Z\sigma_1 \cos \angle Z\sigma_1\sigma_0 \quad (8)$$

to get $Z\sigma_1$, which is the observed zenith distance of σ_1 . Finally, the atmospheric refraction at the large zenith distance can be obtained according to the difference between the observed and the true zenith distance.

3 PROTOTYPE OF A TELESCOPE WITH DOUBLE FIELDS OF VIEW

In order to test the feasibility of differential measurement of atmospheric refraction with double fields of view, a telescope that can observe two sky regions simultaneously is needed. The telescope must meet the critical requirement that the angular distance between the two regions of sky being observed should be fixed. A simple and direct idea that allows the two regions of sky to be observed simultaneously is by using a binocular telescope. However, under the influence of gravity and changes in ambient temperature, the tubes and supporting structure of the binocular telescope will inevitably produce different deformations in the process of measurement, which will change the angular distance between the two fields of view. To this end, the observational principle used by the HIPPARCOS satellite was referenced (Ratier & Batut 1989). The telescope that was used by the HIPPARCOS satellite was an all-reflecting Schmidt telescope that consisted of three mirrors: a beam combiner, a flat-folding mirror and a spherical primary mirror, as shown in Figure 2. The beam combiner was made from a polished Zerodur blank, which was cut into two halves and reassembled with a wedge angle of 29° . The star light from two regions of the sky with an angle of 58° could be reflected to the flat-folding mirror through the beam combiner, and then converged to the focal plane through the spherical primary mirror. This design made it possible to measure the angular distances between stars in two regions of the sky.

Based on the observational principle used by the HIPPARCOS satellite, a double-sided reflective device (we call this the angle reflector) which is similar to the beam combiner can be installed in front of a telescope tube, which can reflect star light from two different directions into one tube, as shown in Figure 3. At this point, the angular distance of the two regions of the sky being observed is only determined by the angle between two reflective surfaces, which can avoid the change caused by the deformation of the telescope tube or supporting structure. A whole piece of Zerodur blank is cut, polished and coated in order to ensure the reflection angle remains constant. The angle of the two reflection surfaces is designed to be 30° , as shown in Figure 4, which can reflect star light from two regions of the sky with an angle of 60° to one direction.

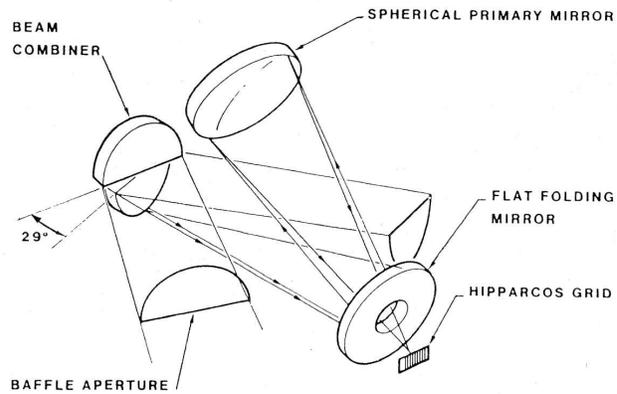


Fig. 2 Configuration of the telescope used by the HIPPARCOS satellite (Ratier & Batut 1989).

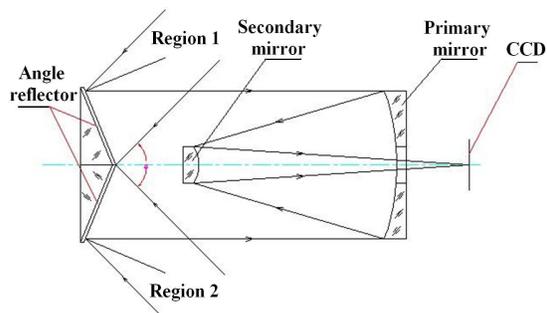


Fig. 3 Configuration of the telescope with double fields of view used to measure atmospheric refraction.

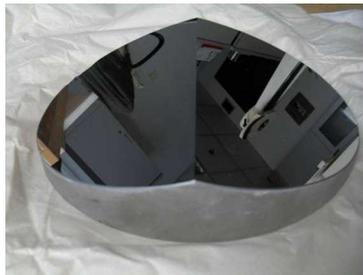


Fig. 4 Photo of the angle reflector.

When carrying out the measurement of atmospheric refraction, the telescope is first pointed to the zenith to collect star light from two sky regions near the zenith (their zenith distances are both 30° or so) and form an image on the CCD camera. Since the theoretical model value of atmospheric refraction near the zenith is accurate enough (better than $0.1''$), the actual reflection angle of the reflector can be determined by the observed positions of the centers of the two fields of view. Then,



Fig. 5 Photo of the prototype of a telescope used for atmospheric refraction with double fields of view.

Table 1 Main Parameters of the Prototype of a Telescope Used for Measuring Atmospheric Refraction with Double Fields of View

Telescope type	Maksutov
Telescope diameter	20 cm
Telescope focal length	2 m
Bottom diameter of reflector	20 cm
Angle of reflection surfaces of reflector	30°
CCD model	Apogee U9000
CCD pixel size	12 μm
CCD array	3056 pixel \times 3056 pixel
Field of view	1.0° \times 1.0°
Pixel scale of CCD	2.5''/pixel@bin2
Operation method	Manual

the telescope is pointed to some value of elevation, e.g. an angle of elevation of 30°. Thus the stars with a zenith distance of 30° and the stars near the horizon can be imaged together on a CCD camera. The atmospheric refraction near the horizon can be calculated according to the principle described in Section 2.

In 2012–2013, we developed a prototype that can measure atmospheric refraction with double fields of view by modifying a Maksutov telescope. We list the main parameters of the prototype in Table 1 and a photo of the prototype is shown in Figure 5.

4 RESULTS OF EXPERIMENTAL OBSERVATION

On 2013 August 9, we carried out an experimental observation with the prototype at Anji station, which is administered by Shanghai Astronomical Observatory. This station is located at a longitude of 119.5976333° and a latitude of 0.4694055°, and the altitude is 943.0 m. The temperature was 24.3°C and the barometric pressure was 906 mbar. First, the telescope was pointed toward zenith to

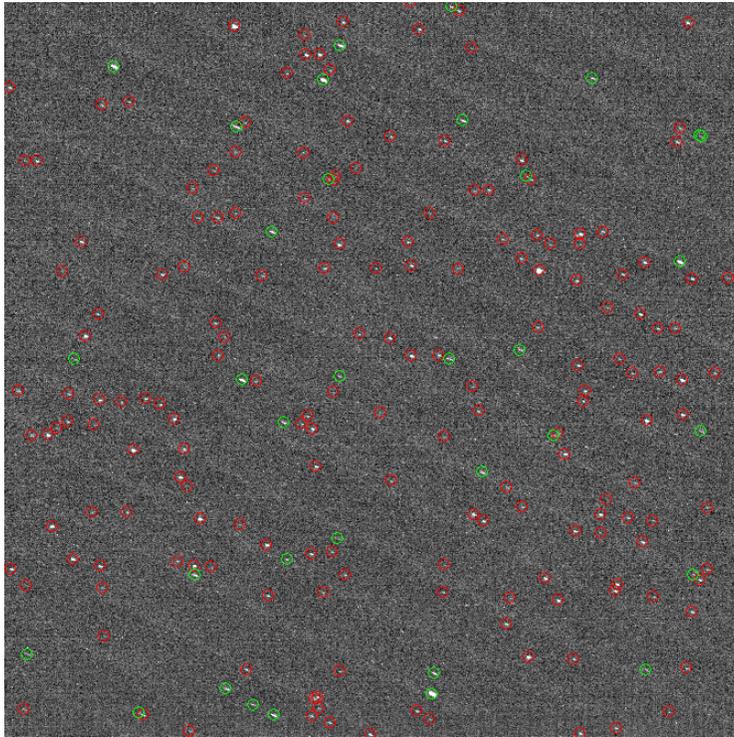


Fig. 6 Example of a CCD image in the case of pointing the telescope toward the zenith.

determine the reflection angle of the reflector. Then, the telescope was pointed toward six directions with different angles of elevation near the azimuth of north and we measured values of atmospheric refraction at the observed zenith distance of 49.4° , 63.9° , 69.0° , 74.1° and 78.8° . To measure the atmospheric refraction at low elevation, due to weak support of the heavy reflector shown in Figure 5, incident light contaminates the signal when the telescope is flexed or moves slightly from the expected direction. However, this does not matter for the refraction calculation, which is determined by star positioning in the double fields with a fixed angle.

4.1 Determination of the Reflection Angle of the Reflector

A total of 15 observations were performed to determine the reflection angle of the reflector. Figure 6 shows an example of a CCD observation image, where the stars marked with green circles and red circles were from the north and south regions of the sky respectively with zenith distances of 30° .

When carrying out observations with double fields of view, stars from the two sky regions were imaged simultaneously. Because the moving velocities and directions of stars from the two regions of the sky were different, the tracking function of telescope could not be used, which makes an efficient exposure time for a star determined by the time that a star image takes to form on one CCD pixel. Given that the moving velocity of the stars from the south region of the sky is faster, their efficient exposure time is shorter, so that the number of observed stars from the south region is less than that from the north region.

Table 2 lists the measured value of the reflection angle according to each observation image. The average is $59.4646413^\circ \pm 0.09''$.

Table 2 Measured Value of the Reflection Angle According to Each Observed Image

No.	Measured value of reflection angle
1	59.4647446°
2	59.4646272°
3	59.4646842°
4	59.4645428°
5	59.4646241°
6	59.4646586°
7	59.4648003°
8	59.4645161°
9	59.4646490°
10	59.4646991°
11	59.4644882°
12	59.4646314°
13	59.4646355°
14	59.4645056°
15	59.4648016°
Average	59.4646413° ± 0.09''

Table 3 Measured Values of Atmospheric Refraction at Different Observed Zenith Distances and a Comparison with the Pulkovo Table

No.	Observed zenith distance	Number of observations	Measured value	Pul. table value	Measured–Pul. table
1	49.4019566°	15	57.63'' ± 0.14''	57.68''	–0.05''
2	63.9007239°	15	100.28'' ± 0.10''	100.60''	–0.32''
3	69.0029459°	15	127.06'' ± 0.13''	128.04''	–0.98''
4	74.0948008°	12	169.90'' ± 0.16''	171.46''	–1.56''
5	78.8301660°	9	240.23'' ± 0.27''	244.11''	–3.88''

4.2 Measured Result of Atmospheric Refraction

The diameter of the Maksutov telescope used in the prototype is smaller and its focal length is longer. Under the influence of atmospheric distortion, it is impossible for the prototype to observe a large number of stars at a given time in a sky region with a low angle of elevation. In order to test the feasibility of operation, only regions of the sky in the north were observed experimentally, where stars move slowly and associated exposure times were relatively long. The telescope was pointed successively to zenith distances of 20°, 35°, 40°, 45° and 50° to get the measured values of atmospheric refraction at zenith distances of 49.4°, 63.9°, 69.0°, 74.1° and 78.8° respectively. We list the results in Table 3, which also gives a comparison of the results with the Pulkovo atmospheric refraction table for reference.

It can be seen from Table 3 that atmospheric refraction at a larger zenith distance can be obtained by the prototype and the average value at the observed zenith distance of 78.8° is 240.23'' ± 0.27''. The experiment indicates that differential measurement of atmospheric refraction with a telescope with double fields of view is feasible. By comparing with the Pulkovo table, it can be seen that the discrepancy between the measured values and the tabulated values increases gradually with the increase in observed zenith distance. The reasons possibly lie in that (1) the Pulkovo atmospheric refraction table is global and it does not consider local characteristics which could be more important at a larger zenith distance. The discrepancy between the measured and tabulated values may reflect the unconformity between the Pulkovo table and the actual local atmospheric refraction; (2) atmospheric refraction is closely related to environmental temperature and pressure. Being subject to

experimental conditions, meteorological data including temperature and pressure cannot be recorded accurately in real time. The errors related to meteorological conditions may introduce some systematic difference between the measured values and values from the Pulkovo table.

5 CONCLUDING REMARKS

It has always been considered difficult to measure the atmospheric refraction at lower angles of elevation. In this study, a new idea for determining atmospheric refraction that utilizes differential measurement with a telescope with double fields of view is proposed. A prototype of a telescope that measures atmospheric refraction with double fields of view was developed by modifying a Maksutov telescope. Our experimental observations were carried out and atmospheric refractions at lower angles of elevation could be obtained by the prototype. Experimental results demonstrate the feasibility of differential measurement of atmospheric refraction with double fields of view.

However, we also found some shortcomings in the prototype in experimental observations. Improvements are needed in the following aspects:

- (1) Limited by the aperture and focal length of the Maksutov telescope, the light gathering ability is inadequate. It is hard for the prototype to observe a sufficient number stars at a lower angle of elevation where there is serious atmospheric extinction. The choice of telescope design should be considered from the perspective of detection ability and observational accuracy.
- (2) A meteorological recording instrument needs to be used when acquiring observations that can provide an accurate record of temperature, humidity and barometric pressure to investigate how these factors affect the accuracy of measuring atmospheric refraction. In addition, the variation in atmospheric refraction as a function of environmental factors can be studied on the basis of long-term measurements.
- (3) The level of automation in the prototype is low and manual control is necessary in observation. The level of automation in image processing and data reduction also needs further improvement.

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