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研究论文

关于地平式反射望远镜的 CCD 平场

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摘要：现有标准设计的反光望远镜在拍摄 CCD 平场时，绝大多数都受残留散射光的影响. 但是赤道式与地平式反光镜所受影响是不同的。在赤道式上做时间序列较差测光时，只要待测星永远位于 CCD 的固定像元上，不太准确的 CCD 平场也能得到高精度的测光结果。当需要 0.1%~0.3% 精度的平场时，则可以采用夜天平场。地平式的特点是，它的 CCD 相机必须置于旋转器上，在跟踪天体时不停地旋转，以抵消地球自转的影响。上述用于赤道式的方法失效，因此，在 CCD 平场时，消除散射光的影响比赤道式更为重要。一个典型的地平式反光镜的例子是 NAOC 兴隆天文台的 EOS 1 米镜. 虽然该台已附加了防散射光的装置，但是对所有 B 、 V 、 R 、 I 滤光片，在不同旋转器位置拍摄的 CCD 平场，仍然有 2%~3% 的差别 (主要是梯度) 。该文给出了改进的建议，必须满足下面两个条件： $C_{ij}=C(r)$; 旋转器的中心与反光镜的光学中心重合。此问题的解决对所有地平式反光望远镜都有普遍意义。

关　键　词：天文观测设备与仪器；反射望远镜； CCD ；平场
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On the CCD Flat Fielding at Altazimuth Mounted Reflector

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Abstract: The CCD flat fielding for the majority (if not all) of existing normal designed reflectors suffers from remains of scattered light. For equatorial mounted reflectors, the very high precision flat fielding is not necessary in differential time series CCD photometry, and the key point is the targets being measured are always placed at the same pixels on the CCD chip. However, the method mentioned above is less effective for altazimuth mounted reflectors, because an altazim-

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uth telescope must be with a field de-rotator to counter the effects of the rotating Earth, and the orientation of the CCD camera relative to the telescope always changes during tracking. Therefore, to eliminate the influence of scattered light in CCD flat fielding for altazimuth telescope is more important than that for equatorial one. In other cases the night sky exposure is necessary if a 0.1% – 0.3% precision flat fielding is required for equatorial reflectors. For altazimuth ones whether a 0.1% – 0.3% precision can be obtained by night sky exposure should be investigated. In our opinion, the following condition should be satisfied: $C_{ij} = C(r, \theta) \equiv C(r)$, which implies that the center of rotater must be coincided with the optical center of the reflector.

The EOS 1-m altazimuth reflector of NAOC at Xinglong Observatory is a typical example which can be used to show the influence. Though this 1-m telescope is mounted additional device by NAOC to eliminate scattered light, unfortunately the CCD flat fields so obtained still show 2% – 3% differences for all the B,V,R and I filters at different rotater positions (primarily as a gradient). Further improvements are suggested. The solution for this problem will have general meaning for all altazimuth mounted reflectors.

Key words: instruments and techniques; reflector; CCD; flat fielding

1 Difference in CCD flat fielding between equatorial and altazimuth mounted reflectors

1.1 $C = C_{ij} = C(r, \theta) \neq C(r)$

In the perfect case, a flat field image would consist of uniform illumination of every pixel by a light source with identical spectral response to that of your object frame [1] (to get "identical spectral" is impossible for broad-band photometry. Which sounds bad, but every night there are some telescopes used to do B,V,R,I broad-band CCD photometry here or there in the world and no complaints have been reported so far). In Surma's paper[2], the uniform illumination of the flat field on the CCD chip is denoted by C. It has been pointed out by Yao et al.[3] that even for an uniform extended light source, C may have a two dimension distribution ($C = C_{ij}$). Here j refers to the row and i the column of the pixel. If a reflector has a camera rotater, then in polar coordinate system $C = C_{ij} = C(r, \theta)$. Where the origin is at the center of the rotater. That is to say, generally C has a pattern. If $C(r, \theta) \equiv C(r)$ (no relation with θ), then C is called as circularly symmetric.

1.2 The main cause of instability of C_{ij} is scattered light

How to show the existence of scattered light? The appearance and influence of scattered light mentioned in our previous paper[4] are as follows:

(1) Pointing the 2.16-m reflector of the Chinese Joint Laboratory of Optical Astronomy (CJLOA) at Xinglong Observatory to the zenith and opening the slit of the dome in the same direction, east, the twilight flat field obtained at dawn was different from that at dusk (different C_{ij} at dawn and dusk), and the quotient of the flat field obtained at dawn divided by that at

dusk mainly shows a gradient. Note the orientation of the slit is set by the engineers always to face east while the 2.16-m is pointed to the zenith, so the only difference between them is the different azimuths of the Sun at dawn and dusk.

(2) Removing the CCD cameras from the 3 optical reflectors (the 2.16-m at Xinglong, the 1.56-m at Zo-se, and the 1-m in Kunming) of CJLOA and place the naked eye at their positions, reflections from the inside of the primary mirror baffles were clearly revealed (in ideal case it should be absolutely black) and not symmetric, among which the least is the Zeiss 1-m reflector and the worst is the 2.16-m.

(3) In Surma's method[2], a series of twilight exposures from short to long time are used to get the flat field and shutter function of the CCD camera simultaneously. In order to get high precision, the shortest exposure should be as short as possible and the longest one as long as possible[2]. If the long exposure is 900s, it belongs to night sky exposure already. This method can be successfully used provided that there is no systematic difference between twilight flat field and night sky exposure, i.e., the pattern $C = C_{ij}$ must be the same (only differs by a factor) for all the exposures. Obviously, here the method considers that the difference in spectral distribution between bright twilight and night sky has no influence on the flat field.

We used Surma's method many times at the 3 optical reflectors of CJLOA. Pointing the reflector to near the zenith and taking a series of twilight flat fields with exposure time from short to long at dusk, or inversly, taking the series of exposures from long to short at dawn, the shortest one being one second and the longest one being 300s, 600s, or even 900s (keep tracking during long exposures and moving reflector slightly between them). The Only success was obtained from the Zeiss 1-m[4]. For this 1-m reflector the sky brightness taking at one second exposure was about 6900 times stronger than that at the 900s. After subtracting the bias and correcting the shutter-timing error all these flat fields can be divided by one another. For all the 3 reflectors the quotients obtained by dividing the short exposures by each other showed homogenous noise image (no variation in C_{ij}, of course it should be so), but only for the 1-m the quotients obtained by dividing a short exposure by the longest one showed almost the same homogenous result (constant C_{ij}). Here the word "almost" means that the inhomogeneity is as small as ($\pm$ 0.1$-$0.2)% (only V filter at the Zeiss 1-m has been tested so far).

Unfortunately, for the 1.56-m and 2.16-m, the quotients showed $>$ 2% inhomogeneity (primarily as a gradient), i.e., the bright twilight flat field is different from the night sky exposure (C_{ij} varies), so the Surma's method can not be used.

These results are not surprising because the 1.56-m and 2.16-m belong to the normal designed reflectors all over the world, which have only two baffles mounted in front of the primary and secondary mirrors, that is not enough to protect the CCD cameras from scattered light (in addition, the baffle of 2.16-m suffers from the light leakage). On the contrary, the Zeiss 1-m belongs to the few reflectors in the world, which not only has the normal standard primary and secondary baffles, but also is enclosed by a thick metal tube just like a refractor.

Therefore, it is mainly scattered light (not the difference of spectral distribution between twilight and night sky exposures) which induced the variation of C_{ij} and the failure of Surma's method.

It is well known that the best uniform extended light source to get flat field image is the night sky exposure. The disadvantage of night sky exposure is the too low pixel signal to noise ratio, and in order to get enough precision a large number of night sky exposures (may be the whole night) must be spent. If Surma's method can be used, combining the bright twilight with the night sky exposures can get high precision flat field. Otherwise, "For applications requiring better than $0.1\% - 0.3\%$ flat-fielding, we recommend (as always) that flat fields be constructed from dark sky exposures"[5].

(4) Tobin[6] in 1992 put a camera at the position of the CCD chip to get the photograph of the secondary mirror and its surrondings to show the existence of scattered light at the McLellan (equatorial) 1-m of Mt John University Observatory (MJUO).

Grundahl and Sorensen[7] in 1996 made a pinhole camera to detect scattered light at the 2.56-m Nordic Optical Telescope (NOT). In its pinhole image scattered light has a obviously asymmetric distribution, i.e., $C = C_{ij} \neq C(r)$.

We imitate them to get the pinhole images of the 1.56-m at Zo-Se and the 63-cm reflector of the Nanjing University and obtained similar asymmetric results.

Just because the intensity and asymmetric distribution of scattered light are different during flat field observations, the C_{ij} varies.

1.3 Difficulty in precise CCD flat fielding at altazimuth reflector and consequence of $C \neq C(r)$

The altazimuth mounted reflector must have a field de-rotator to counter the effects of the rotating Earth, so the orientation of the CCD camera always changes relative to the telescope during tracking. If the $C_{ij} = C(r, \theta) \neq C(r)$, then the object frames observed at different directions need different flat fields. But it is impossible to do so, which causes the resultant CCD photometry suffers from systematic error!

Equatorial reflectors are not the case. For example, although the C_{ij} at the Zeiss 1-m is stable among twilight and night sky flat field exposures, the quotients of two flats obtained at different rotater positions show patterns[4], i.e., $C_{ij} \neq C(r)$. We still do not know why $C_{ij} \neq C(r)$. If there exists small remaining scattered light and it is reduced or eliminated by modifying the baffles of Zeiss 1-m, whether the C_{ij} will become circular symmetric or not. In other words, is scattered light the unique cause to produce the asymmetric distribution at this 1-m?

One possibility is that the center of the rotater does not coincide with the optical center of the 1-m, because C_{ij} is not symmetric relative to the center of the rotater, even it is circular symmetric relative to the optical center. Further investigations are needed[4].

However, this problem is not important for equatorial reflectors if both the object and the flat field exposures are obtained at the same CCD rotator position.

For equatorial mounted reflectors, the very high precision can be obtained in differential time series CCD photometry even though the flat fielding is not accurate, because the key point here is the stars being measured are always fixed at the same pixels on the CCD chip.

But for an altazimuth reflector, even the stars being measured are always fixed at the same pixels on the CCD chip, the magnitude difference between a comparison star and a variable in differential photometry may have a systematic error superposed on the variable's light curve. Depending on the continuous variation of the CCD camera position relative to the reflector, this kind of systematic error is periodic. When the telescope is pointed to a given hour angle and δ (a given altitude and azimuth) on the sky, the CCD camera is also rotated at a given angle, so the same systematic error is suffered. If a variable star is observed successively for several nights, the spurious period is one day.

Note, for example, the main period of δ Sct variable stars is with an amplitude of only several hundredths of a magnitude and other periods with amplitudes less than 0.01 mag. The periodic systematic error so introduced is not acceptable.

If an open cluster is observed in order to get the C-M diagram of the cluster, the magnitudes so obtained may suffer from systematic error depending on star positions on the CCD chip.

In sum, if high precision CCD photometry is needed, much more efforts in eliminating scattered light should be made at altazimuth reflectors than at equatorial ones. The final destination is to get $C_{ij} = C(r, \theta) \equiv C(r)$.

2 Reported examples to reduce scattered light in literature

Although to prevent optical instruments from scattered light is an old classical problem, to eliminate it is not easy at all. Very much accurate flat fielding is unnecessary for some kinds of works. A flat field as accurate as $2\% - 3\%$ may be enough for them. But there are many other works where flat fielding as accurate as possible is needed.

Grundahl and Sorensen[7] were the first to make a simple but effective pinhole camera to detect scattered light at the altazimuth mounted 2.56-m NOT and correct it by adding annuli inside the primary baffle.

Later, similar to NOT, Gutierrez et al.[8] made the same kind of detection and correction at the 2.1-m (altazimuth mounted) San Pedro Martir reflector.

Barnady and Rauscher[9] also used the pinhole camera method to detect scattered light at the Cerro Tololo Inter-American Observatory (CTIO) 0.9-m (equatorial) reflector and correct it by adding 3 baffles.

Annuli were also added in the telescope baffles of the McLellan (equatorial) 1-m at MJUO[10].

No modifications in telescope baffles at Kitt Peak National Observatory (KPNO) were reported. Therefore, for deep CCD surface photometry of galaxy clusters at the (equatorial) 2.1-m of KPNO, "in order to reduce scattered light from the mounting hardware surrounding the CCD", Feldmeier et al.[11] had to place "a black cardboard mask over the detector's Dewar window", and "next took pinhole images of the telescope pupil to search for other sources of scattered light and baffled any such areas with black cloth." Obviously this is a temporary measure. But they have done surface photometry down to a surface brightness of $\mu_v = 26.5$ mag arcsec^{-2}.

This may be the best example in eliminating scattered light. However, it seems that the problem is not solved thoroughly at other telescopes. We have not read the result at the CTIO 0.9-m so far, but the other telescopes mentioned above only reported the significant reduction of scattered light, not the complete elimination of it.

Although the baffles of the McLellan 1-m have been modified, in differential photometry "targets were always placed at a fixed location on the detector in order to eliminate the effect of any systematic errors in the flat fielding correction"[10].

For the NOT observations, Grundahl et al.[12] estimated the errors in the flat fielding to be less than 1% (not $0.1\% - 0.3\%$).

In order to achieve the highest possible precision in differential photometry at NOT, Bruntt et al.[13] obtained their working flat field by combining all twilight flat field images observed at different rotations of the CCD camera relative to the telescope. In addition, they also keep the stars in the same position on the detector. Even so, We are afraid the precision may be worse than that at an equatorial one.

Although Massey et al.[5] at KPNO recommend for applications requiring better than $0.1\% - 0.3\%$ flat-fielding the flat fields should always be constructed from dark sky exposures. If the night sky exposure is used to make the flat field at altazimuth mounted reflectors, can the $0.1\% - 0.3\%$ precision flat fielding be achieved? Here the key point is: to the $0.1\% - 0.3\%$ precision, C_{ij} must be $\equiv C(r)$. Otherwise a flat field made of night sky exposure at one CCD camera position should not be used in flat fielding the object frames at other positions.

Can it be achieved at altazimuth reflectors? It seems still an open question for the time being.

3 On the EOS 1-m reflector of NAOC at Xinglong

The EOS 1-m of National Astronomical Observatories (NAOC) is an altazimuth mounted reflector with Nasmyth foci, delivered to Xinglong in 2005. Though it is a new reflector, we suppose the designers of this reflector did not read the related papers published in literature since 1996, so the reflector is still a normal designed one. This 1-m has been mounted additional device by NAOC to reduce scattered light, and it is important to check whether the CCD flat fields so obtained suffer from scattered light or not.

3.1 Testing the stability of C_{ij} in twilight exposures without camera rotation

In order to test if Surma's method is feasible at the EOS 1-m, we set the telescope at $\delta = 43^\circ$ and hour angle $\approx +40^{\mathrm{m}}$ to aviod the blind region near the zenith (the latitude is $40^\circ.39$), and the similar series of twilight exposures from short to long were made for the B,V,R and I filters together. Here the CCD camera did not rotate too much. All the quotients obtained by dividing a short exposure by the longest ones show almost homogenous noise image with the inhomogeneity as small as $\pm(0.2 - 0.6)\%$. It means that at this precision C_{ij} is stable during twilight exposures, with no relation to the difference in spectral distribution between bright twilight and night sky exposure. It is shown that the additional device mounted at the EOS 1-m by NAOC is useful. The results are much better than that obtained at the 2.16-m reflector of NAOC[3,4].

The quotient images for B,V and R band are shown in figure 1. (The quotient image for I band is not shown because we haven't eliminate the fringe pattern in the long exposure image). Here the exposures were: 4s,4s,5s for short exposure, and 70s,120s,150s for long exposure for B,V and R separately. Forget the star images in the figures due to long exposure and notice the background only. The scans along the diagonals of each subimages of figure 1 are shown in figure 2, where the unit in the X axis is the number of the pixels, and the y axis the ratio of two corresponding images.

3.2 Difference among flat fields obtained at different rotater positions

In order to check if the flat fields obtained at different rotator positions are different, the following exposures were made:

(1) To set the telescope at $\delta = 43°$ and hour angle $\approx -40^{\mathrm{m}}$ (before meridian), short exposures from 0.5s to 2s were obtained for B,V,R and I filters.

(2) After that, immediately set the telescope at $\delta = 43°$ and hour angle $\approx +40^{m}$ (after meridian), so the telescope quickly moved to the new position and the CCD camera also quickly rotated relative to the telescope by almost 180°, exposures from 4s to 8s were obtained.

In this process the telescope was always pointed near to the zenith and the spectral distribution (the color) of the sky did not change a lot.

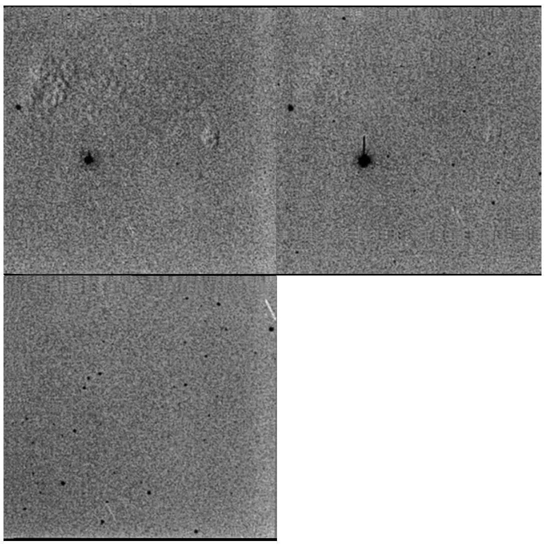

图 1　From upper left to right, in order of B, V, R, quotients of one twilight flat field (long exposure) divided by another (short exposure) at the EOS 1-m on 2007.8.8

Then the frames so obtained were subtracted by bias and corrected by the shutter-timing error and divided by each other for each filter. Quotients of two exposures obtained at the same camera position are all homogenous noise images. However, the frames obtained before meridian divided by that after meridian show about $2\% - 3\%$ differences for all the 4 filters (primarily as a gradient plus weak pattern) as shown in figure 3. Here the exposures were: 2s,2s,2s,2s before meridian, and 4s,4s,5s,8s after meridian for B,V,R and I separately. The scans along the diagonals of each subimages of figure 3 are shown in figure 4.

It means that the $C_{ij} = c(r, \theta) \neq C(r)$ (not circular symmetric).

How to explain the weak pattern in figure 3?

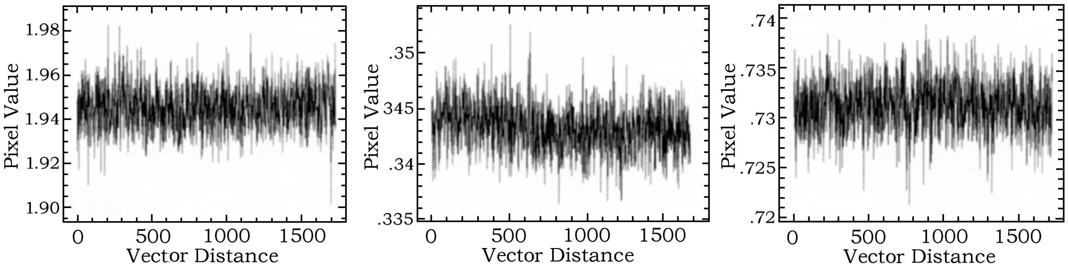

图 2 Scans along the diagonals of each subimages of figure 1

In our opinion this is the evidence that the center of the CCD camera rotater does not coincide with the optical center of the reflector.

Inspect the small rings in figure 3, which are the images of the dust or the condensed small moisture drops which are adhered on the surface of the CCD camera window. In the series of flat field exposures, their positions on the window are fixed, so their images (rings) are also fixed on the flat field images when the rotater of the reflector does not rotate. When the rotater is rotated by 180°, if the $C_{ij} = C(r)$ and the center of rotater coincides with the optical center of reflector, the positions of these rings should be fixed on the flat field images. However, comparing the flat field images obtained before and after meridian, there are shifts between the rings obtained before and after meridian. The length of the shifts is about 13 pixels (pixel size 20 micron), corresponding to 0.26 mm on the CCD chip. When the flat field obtained before meridian is divided by that after meridian, these rings can not be canceled on the quotient image.

4 Discussion and suggestions

We suggest that the pinhole image of the EOS 1-m should be got in order to inspect the sources of scattered light and eliminate it. The 2.56-m NOT and the 2.1-m San Pedro Martir reflector only modified the primary baffles. But the CTIO 0.9-m has added 3 baffles. The KPNO equatorial 2.1-m made more measures to eliminate scattered light and got the best result. If more measures are made (modifying the primary baffle and other parts) at the EOS 1-m, at least the precision of flat fielding should be improved from the present $2\% - 3\%$ to less than 1%. If the remaining scattered light is reduced or eliminated by modifying the primary baffle and other parts, can the $0.1\% - 0.3\%$ precision be achieved? We think that two conditions should be satisfied:

(1) If the origin of the C_{ij} is set at the optical center of the telescope, when scattered light is eliminated, one may expect that the C_{ij} becomes circular symmetric relative to the optical center, $C_{ij} = C(r^{'})$, where $r^{'}$ means it is at a coordinate system with the origin at the optical center of the telescope. This is the first and basic requirement, but not enough, unless the $C(r) \equiv C =$ constant.

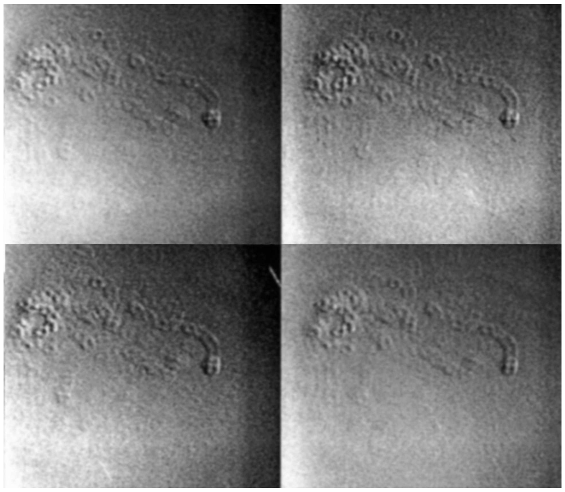

图 3 From upper left to right, in order of B, V, R, I, quotients of one twilight flat field (before meridian) divided by another (after meridian) at the EOS 1-m on 2007.8.8

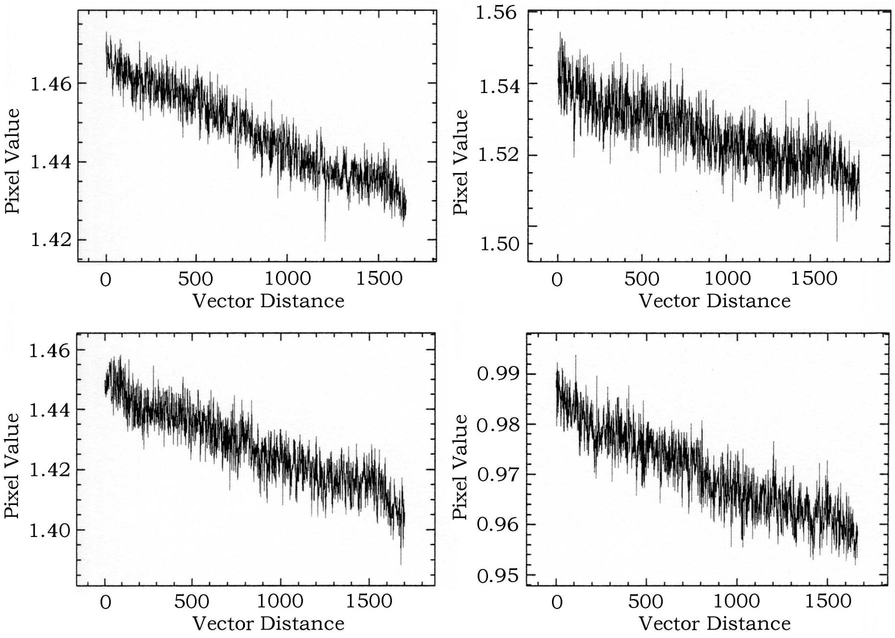

图 4 Scans along the diagonals of each subimages of figure 3

(2) the center of the rotater should be coincided with the optical center of the reflector, then $C_{ij} = C(r)$. In fact, the origin of the C_{ij} which we discuss is defined at the center of the rotater. It may be not easy to set the center of the rotater in order for it to be coincided with the optical center of the reflector. If they are not coincided with each other, $C_{ij} \neq C(r)$, then the expected flat fielding precision can not be achieved (note that whether the center of the CCD chip is coincided with the center of the rotater is not important). In addition, as mentioned above, the dust grains droped on the surface of the CCD camera cause the local change of the flat field, which can not be eliminated by dividing the flat field.

As far as we know, no such high precision flat fielding has been achieved at any altazimuth mounted reflectors. To investigate this problem will have general meaning for all altazimuth mounted reflectors all over the world.

Acknowledgments:

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