Configuration for Chinese Future Giant Telescope

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ABSTRACT

This telescope has 30m aperture, segmented primary mirror and alt-azimuth mounting. The aspherical primary mirror with f-ratio 1.2 consists of 1122 partial annular submirrors. The optical system includes Nasmyth I and II systems, Cassegrain system, coude system and a wide field of view system. There are four Nasmyth platforms. Two Nasmyth I foci are located on the upper floor and two Nasmyth II foci are located in the lower floor. All Nasmyth I, II and Cassegrain systems use same one secondary mirror, and all are R-C systems. With adaptive optics system, several diffraction-limited observations can be operated simultaneously on Nasmyth II platforms. The wide field of view system has 20 arcmin FOV, can correct atmospheric dispersion and the low space frequency error from primary mirror and atmosphere turbulence. A special rocking chair structure is designed which can realize the horizontal axis on the front of primary mirror. The tolerances of the surface shape and position of submirrors are given. The issues about tip-tilt correction and adaptive optics are discussed. Some formulae on rotating conic surface especially used for segmented mirror are given.

Key words: Astronomical optics- Telescope- Future Giant Telescope- Extremely Large Telescope

1. INTRODUCTION

Today by using 8-10m telescopes and Hubble Space Telescope a few events in early universe have been observed. Also more than one hundred Jupiter-like planets have been observed by these and other telescopes. These stimulate the astronomers and popular people strongly to hope to observe more events in the early universe including the first generation of galaxies to be assembled and to shine in the dark universe i.e. to see the dawn of modern universe, to research star and planet formation, to study black hole, to explore the earth-like planets in nearby stars. These observations need much larger ground-based and space telescopes, which have larger collecting area for light and higher resolution. Technically, the success of segmented-mirror telescopes Keck I and II created a possibility to build much larger telescopes, and the success of adaptive optics showed the diffraction-limited image could be obtained in ground-based telescopes at least in IR wave band. By using larger ground-based telescope not only more light energy could be collected, but also the higher resolution can be reached. Thus the studies of Extremely Large Telescope (ELT) or called Future Giant Telescope (FGT) have already become one of the most active areas in observational astronomy and astronomical technology. Some projects such as CELT[1], OWL[2], GSMT[3] etc. have been already put forward. We have also done some researches on configuration of FGT[4,5]. In this paper, a new configuration for Chinese Future Giant Telescope（CFGT）and many researches around it are given.

In last century China developed many astronomical telescopes even they are smaller but almost all of them are developed by China himself and until now they are the main facilities for Chinese astronomy. Now several new astronomical facilities are being developed in China. Through these activities many astronomical telescope experts have grown. Recent more than twenty years Chinese economy has an unprecedented progress. The poor times of China has gone. Relevant to FGT, Recently an annular polishing machine has been equipped in NIAOT, National Astronomical

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Observatories, Chinese Academy of Sciences. Some researches on FGT have being done in China. A site survey in west China including Tibet has begun. It is hopeful to find an ideal site where the 30m even more optical/IR telescopes could be installed.

We think the following requirements should be satisfied for CFGT:

a. The possibility of building such a telescope should be put on a very important position.

b. The most important working waveband for this telescope is infrared waveband. In our configuration, all systems consist of reflecting mirrors and the secondary mirrors are the stops except wide FOV system.

c. Its main foci should be on the platforms where the gravitation is unchangeable and each of these platforms has enough large area. The complex follow up optical systems, adaptive optics systems and various instruments can be installed there.

d. This telescope could join with other telescopes to form an interferometric array. From such an array, the resolution much higher than one unit telescope could be obtained. In our configuration, there is a coude system for this purpose.

e. A wide FOV system has 20 arcmin FOV and seeing-limited image quality is necessary. It is used for the multi-object fiber spectroscopic observation.

CFGT is a 30m telescope with segmented primary mirror and alt-azimuth mounting. The primary mirror is aspherical, with f-ratio 1.2, and consists of 1122 partial annular submirrors. The size of submirror is about 0.8m $\times$ 0.8m. This telescope includes Nasmyth I and II systems, Cassegrain system, coude system and a wide field of view system. There are four Nasmyth platforms. Two Nasmyth I foci are located in the upper floor and two Nasmyth II foci are located in the lower floor. All Nasmyth I, II and Cassegrain systems use same one secondary mirror, and all are R-C systems. In wide FOV system there is a deformable mirror, the image of primary is on it, which can correct the low space frequency error from primary mirror and atmosphere turbulence. In order to avoid adding much counterweight at the back of primary mirror in this telescope the horizontal axis is at the front of primary mirror. A special rocking chair structure realizes such a requirement successfully. This mechanism also realizes four big Nasmyth platforms. By exchanging the above part of tube two secondary mirrors and the wide FOV system can be moved on or moved off.

2. OPTICAL SYSTEM

At vertex of primary mirror the radius of curvature is 72m and the focal length is 36m. If the clear aperture is 30m the f-ratio is 1.2. But since the secondary mirror is taken as stop actual f-ratio of primary mirror is a little larger than 1.2.

2.1 Nasmyth system

There are two kinds of Nasmyth system in this telescope (Fig.1). Nasmyth I system is a traditional one. It feeds the light to the two traditional Nasmyth platforms. The magnification of secondary mirror m= -15. In CFGT the horizontal axis is chosen 3m above the vertex of primary mirror and the Nasmyth I focus is chosen 2m out of the edge of primary mirror. b expresses the distance from the vertex of primary mirror to focus ignoring all planar mirrors. So in Nasmyth I system b=14m. In CFGT two options (including three methods) are considered to design the two-mirror system: (1) Ritchey-Chrétien system: a. According to the definition of Chretien[6] R-C system is a two-mirror system, which is free from spherical aberration and satisfies sine condition for all rays parallel to the optical axis. In 6 Chrétien give the differential equation and a power series solution for such a system. We[7] extent Chrétien's idea and wrote a program to calculate the shapes of two surfaces (adjacent or not) in an optical system simultaneously to make the system free from spherical aberration and to satisfy sine condition for all rays parallel to the optical axis. In this program we take the conic curve adding high-order power polynomial for the section of two surfaces. b. According to eliminate three-order spherical aberration and coma an approximate solution of R-C system can be obtained. In Section 6 we give such a solution in formula (3), in it we take the conic curve for the section of two surfaces. Such a solution (3) is independent of the position of entrance pupil. (2) Optimizing the two-mirror system by using the merit function which consists of RMS of image spot. In this calculation we also take the conic curve adding high-order power polynomial for the section of two surfaces. The results are: even the f-ratio of primary mirror is as strong as 0.6 the above three solutions have almost the same image quality. In CFGT we decide to choose R-C system for Nasmyth I, II and Cassegrain systems, to choose the conic rotating surfaces for all surface of mirrors, and using Section 6 formula (3) to obtain the conic constants k_1 and k_2 for primary mirror and secondary mirror.

According to formula (3) we obtain k_1= -1.00084495, k_2 = -1.31809465. Since infrared is the most important waveband for all systems except wide FOV system for this telescope, the stop is the secondary mirror. Since Nasmyth I, II and Cassegrain systems use a same one secondary mirror the smallest secondary mirror should be chosen as a stop that is Cassegrain secondary mirror. The diameter of it is 2476mm. According to m= -15, b=14m, we obtain: at the vertex of secondary mirror the radius of curvature r_2 = -6696.4286mm. The distance from primary mirror to secondary mirror d = -32875mm. In an optimal spherical focal surface with radius -3235.6917mm the spot diagrams of this system is shown in Fig.2. The largest image spread in FOV 2.51 arcmin is 0.0084 arcsec, which is the diameter of Airy disk at 0.5 micron wave length, and the largest image spread in FOV of 8 arcmin is 0.086 arcsec. In this situation the diameter of entrance pupil is 28420mm. So the f-ratio of Nasmyth I is 19. The clear aperture of primary mirror is 29305mm for FOV 8 arcmin.

Nasmyth II includes primary mirror, secondary mirror and three fold planar mirrors (Fig.1). After reflected by secondary planar mirror the ray is along the vertical direction to the next floor platform. Then the light is reflected by third planar mirror, which is movable on the platform for choosing the observing area, along horizontal direction into the following optical system. In optical design the difference between Nasmyth I and II are only b= 14m and b= 26m. The method to change the surface shapes of mirrors to improve image quality were put forward in[4,5,8-10] and used in ESO VLT primary mirror. This method is used in CFGT. Moving secondary mirror along optical axis, changing r_2 to make the focus at b= 26m, and changing k_1,k_2 to make each system is R-C system (using formula (3)) then we can find a system in which the deviation from this secondary mirror to the original one (secondary mirror of Nasmyth I) is minimum. Such a system is chosen as Nasmyth II, in it r_2 = -6700.4102, d = -32830.300mm, k_1= -1.00056054, k2 = -1.24827666. From Nasmyth I to Nasmyth II the secondary mirror is moved towards primary mirror 44.70mm. According to r_2 and k_2 of Nasmyth I and II using the conic curve formula (2) in Section 6 the difference of two surface shapes of secondary mirror are obtained. It is shown in Fig.3 and the maximum difference of it is 16.9 µm. It is no problem to realize such a change by using active optics method. According to the k_1 of Nasmyth I and k_1 of Nasmyth II using the conic curve formula (2), the difference of these two surface shapes of primary mirror are obtained. The largest displacement of submirrors is 0.0043 mm, which is in the most outer ring of primary mirror. The maximum of submirror change at the diagonal edge of most outer ring. It can be calculated by put Δk_1 into (6) to obtain Δr_1, Δr_2, then put them into (8), the largest change of submirror z = 26 nm is obtained. Such a deformation is very small, the diffraction-limited image can be obtained by only moving submirrors i.e. two set readings of displacement sensors, which are used for controlling the 16 angels of each two submirror rings see Fig.10, are prepared for Nasmyth II and I respectively and by using displacement actuators to change 16 angels of each two submirror rings. In this Nasmyth II system the stop also is the secondary mirror, the diameter of it still is 2476mm. The diameter of entrance pupil is 28037mm. The f-ratio is 23.83. The clear aperture of primary mirror is 28908mm for FOV 8 arcmin. In an optimal spherical focal surface with radius -3337.6224 mm the pattern of spot diagram of Nasmyth II is similar to Nasmyth I, the largest image spread is 0.0084 arcsec in FOV 2.83 arcmin and the largest image spread is 0.069 arcsec in FOV of 8 arcmin. Since the main aberrations of R-C system are astigmatism and field curvature, in a small sub-region of FOV these aberrations are easy to be corrected by following optical system and with adaptive optics system several diffraction-limited observations can be operated simultaneously. In our configuration Nasmyth II platform can be rotated about the vertical principal ray, which from second planar mirror, thus the rotation of field of view can be compensated for all instruments on this platform at the same time. This is an important advantage of Nasmyth II.

2.2 Cassegrain system

Cassegrain system only includes two mirrors and in there no extra-polarization is caused by optical system (Fig.1). These are two important characters. In this configuration the Cassegrain focus is chosen at 3m behind the vertex of primary mirror i.e. b = 3m. In CFGT the Cassegrain system also is an R-C system and use the same one secondary mirror with Nasmyth I and II. Similar to Nasmyth II we obtain such a Cassegrain system, in it r_2 = -6690.1782 mm, d= -32939.744mm, k_1= -1.00134720, k_2= -1.42764944. From Nasmyth I to Cassegrain the secondary mirror is moved towards prime focus 64.74mm. The difference of two surface shapes of secondary mirror of Cassegrain and Nasmyth I is shown in Fig.3. The maximum change of it is 26.6 μ m. In primary mirror the largest displacement of submirrors is 0.0076 mm. And the largest change of submirror is 46 nm. Such a deformation still is small, the diffraction-limited image can be obtained by only moving the submirrors. In this system the stop also is the secondary mirror and the diameter of it still is 2476 mm. The diameter of entrance pupil is 28994mm. The f-ratio is 14.58. The clear aperture of primary mirror is 29900 mm for FOV 8 arcmin. In an optimal spherical focal surface with radius -3107.0907mm the pattern of spot diagram of Cassegrain system is similar to Nasmyth I, the largest image spread is 0.0084 arcsec in FOV 2.17 arcmin and the largest image spread is 0.11 arcsec in FOV of 8 arcmin.

It should be pointed out that if in above Nasmyth II and Cassegrain systems only spherical aberration can be eliminate (not an R-C system). In this situation the image quality has a little worse and coma is existent but only the surface shape of secondary mirror need to be changed and the error of the change of primary mirror is completely avoided.

2. 3 Another configuration for Nasmyth II system and Cassegrain system

From Nasmyth I to Nasmyth II and Cassegrain the common secondary mirror will change its surface shape 16.9 μ m and 26.6 μm respectively. If this mirror has a medium stiffness by using about 40 actuators the diffraction-limited surface shape could be obtained for Nasmyth II and Cassegrain systems. This secondary mirror may also used as an adaptive mirror. In this situation the stiffness of secondary mirror should be much lower and there are much more than 40 actuators on the back of it. The required shape of secondary mirror can be also obtained by using these actuators, but the dynamic range of actuators should be increased greatly. In this situation if only using about 40 actuators since the stiffness is much lower the shape obtained will be bad. This is a contradiction.

We considered another configuration that is to add two secondary mirrors one for Nasmyth II and another for Cassegrain system. We find: the shape of primary mirror is unchanged as in Nasmyth I, if a proper magnification m of secondary mirror is chosen an R-C system can be obtained for Nasmyth II system. The method is to put k_1 of Nasmyth I and b= 26m into formula (3) (attention $f = mf_1$, f_1 is constant, which equals -36000mm) the magnification m can be obtained. Using such an m the Nasmyth II is an R-C system. In this system, r_2= -7674.5420mm, d=-32399.321mm, k_1=-1.00084495, k_2 =-1.29032473. In this system the stop is the secondary mirror, the diameter of it is 2925mm. The diameter of entrance pupil is 29143mm. f-ratio is 20.04. The clear aperture of primary mirror is 29900mm for FOV 8 arcmin. In an optimal spherical focal surface with radius -3793.2457mm the pattern of spot diagram of this Nasmyth II is similar to Nasmyth I, the largest image spread is 0.0084 arcsec in FOV 2.77 arcmin and the largest image spread is 0.071 arcsec in FOV of 8 arcmin.

Similarly, such an R-C Cassegrain system also can be obtained. In this system, r_2= -5717.5194mm, d = -33349.6777mm, k_1= -1.00084495, k_2= -1.35372885. In this system the stop is the secondary mirror, the diameter of it is 2132mm. The diameter of entrance pupil is 28842mm. f-ratio is 17.12. The clear aperture of primary mirror is 29900mm for FOV 8 arcmin. In an optimal spherical focal surface with radius -2699.9166mm the pattern of spot diagram of this Cassegrain system is similar to Nasmyth I, in FOV 2.28 arcmin the image spread is less than 0.0084 arcsec and the largest image spread in FOV of 8 arcmin is 0.11 arcsec.

2.4 Coude system

In order to do the interferometric work with other telescopes it is important to include a coude system in CFGT. The preliminary consider for this coude system (Fig.4) are: taking b= 500m, f-ratio is 200 and FOV is 30 arcsec. If moving secondary mirror along optical axis to make the final focus to the coude focus, one will find the displacement of secondary mirror is big. And if we hope this coude system is an R-C system the change of surface shape of secondary mirror and the deformation of submirrors of primary mirror all are much bigger than above from Nasmyth I to Nasmyth II and Cassegrain systems. Even the coude system is only free from spherical aberration both the displacement of secondary mirror and the change of surface shape of secondary mirror (the surface shape of primary mirror is unchanged) are still bigger. So we decide to use a new secondary mirror for coude system. In this coude system the stop still is secondary mirror, the diameter of it is 2652mm. The surface shape of primary mirror is unchanged as in Nasmyth I. In such a coude system only spherical aberration is eliminated. In it, r_2= -6432.2315mm, d=

-32803.181mm, k_1= -1.00084495, k_2=-1.03397912. The diameter of entrance pupil is 29847mm. f-ratio is 201. The clear aperture of primary mirror is 29900mm for FOV 30 arcsec. In an optimal spherical focal surface with radius -3546.7115mm the spot diagram for this system is shown in Fig.5. In FOV 29.59 arcsec the largest image spread is 0.0084 arcsec, which is the diameter of Airy disk at 0.5 micron wave length.

In 5 we put forward a method: in an optical system changing the surface shape of planar mirror into aspherical to improve the image quality. This is an effective method. For example, if we change the surface shape of second fold planar mirror of coude system, the field of view could reach about 4 arcmin in which the largest image spread is 0.0084 arcsec. In this system, the primary mirror is unchanged as in Nasmyth I, the secondary mirror still is a rotating conic surface and the asphericity of original second planar mirror is only about 0.7 µm.

2.5 The wide field of view system

According to science goal, a wide FOV system with about 20 arcmin FOV and seeing-limited image quality is necessary. It is used for the multi-object fiber spectroscopic observation. This system should satisfy three requirements: (1) seeing-limited image quality i.e. the light energy concentrated in about 0.5 arcsec. (2) Correcting the atmospheric dispersion. (3) Correcting the low frequency wavefront error from primary mirror by wind and from atmosphere turbulence. From the consideration of optical design such a wide FOV system should be installed near prime focus. Both reflecting and refracting optical components should be used to compose such a system. In many references for example[11- 14] two concave mirrors are used as a corrector and this corrector is also used recent in HET and other telescopes. Such a two-mirror corrector, a pair atmospheric dispersion correcting prisms and four lenses are used in GSMT wide FOV system[3]. The design of it is a masterpiece, which is designed by our friend and old colleague Ming Liang, and it is a main reference during we design our wide FOV system. Our system is shown in Fig.6. In it the diameter of mirror A is 2.2m. It may be also used as a tip-tilt mirror. In this system the mirror A forms the image of primary mirror on mirror B. The image diameter of it is 1.6m and this also is the diameter of mirror B. The mirror B is a deformable mirror of adaptive optics. On mirror B the image diameter of each submirror is about 42mm×42mm. The entrance pupil is taken at infinite i.e. a telecenter system, the conic angle of ray equals 20 arcmin in diameter, a series objective points are taken on a section of primary mirror. The images of these objective points formed by mirror A on the surface of mirror B are calculated. The image diameter is only 2 mm for the point on the vertex of primary mirror and the largest image diameter is 34 mm for the edge point of primary mirror. The most main aberration is curvature of field. If we put mirror B at the average position the largest image diameter could be less than 10 mm. Such an image quality is satisfied for installing about 1000 actuators at the back of mirror B. There is a pair of lens-prisms[15- 17] with largest dispersion 4.26 arcsec (in this wide FOV system design, we take the waveband is 350nm-1014nm). It can correct the atmospheric dispersion until z= 70° at 4500 m sea level. The diameter of two lens-prisms is about 750mm and use Schott glass BK7 and LLF6. In our system the image surface is a spherical with radius about -1294mm, although it is no big problem for installing fibers this is still a shortcoming. Fig.7 gives the spot diagram of this system when observing zenith (z= 0°), the 100% geometry energy is in 0.36 arcsec. Fig.8 gives the geometric encircled energy of this system when observing zenith distance 70° , 90% geometric energy is in 0.77 arcsec. There is a baffleplate between mirror A and mirror B (see Fig.6). The baffleplate obstructs about 0.45 in diameter of light beam or 20% light energy. The f-ratio of this wide FOV system is 2.06. The linear diameter of FOV is about 364mm, we hope more than 2000 optical fibers can be put on it. We intend using a part (may be about 100mm in length) conic optical fiber to change the f-ratio from 2.06 to 5 then into the constant diameter optical fiber. If the diameter of optical fiber is taken as 0.7 arcsec. The entrance diameter of conic fiber will be 0.224mm and the exit diameter of conic fiber, i.e. the diameter of rest constant diameter fiber, is 0.509mm.

During design this wide FOV system, a new idea is emerged in our brain that is: using the submirrors of primary mirror to do the tip-tilt movement to correct the wind attack on the primary mirror and the atmospheric turbulence. It is unnecessary to add any new mechanism. Since the size of submirror is only 0.8m x 0.8m and only tip and tilt (don't include piston) are corrected, it is no big difficult to promote the correcting frequency to 20 Hz even more. Such a method is not suitable for co-phase correction so the diffraction-limited image can not be obtained. But it is valuable for such a wide FOV system. If thus, mirror B is unnecessary to be used as a deformation mirror of adaptive mirror and better correcting result may be obtained.

3. SUBMIRROR AND ALIGNMENT TOLERANCE

The ideal method for fabricating submirrors is: first, using an annular polishing machine with stressed-mirror method and ion polishing method to fabricate convex molds for all different kinds of sub-mirrors; then, using replication method to obtain all submirrors. For our annular polishing machine the largest size could be polished is about 1.2m. If 30m primary mirror consists of hexagonal submirror with 1m diagonal length, there will be about 100 different types in surface shape. It is not convenient and is expensive. Instead of the hexagonal submirrors we intend to use the partial annular submirror for the primary mirror of CFGT. Each submirror is 0.8m along radial direction and about 0.8m in circle of partial annular direction. The area of this submirror is about the same as the former hexagonal one. The approximate shape of it is a 0.8m x 0.8m rectangle (about 1.13m in diagonal direction). An original arrangement is given in 5. An improved arrangement considered by Dehua Yang is shown in Fig.9. There is a center hole with diameter 2.8m at the center of this primary mirror. The total number of submirrors is 1122 and distributed in 17 rings. There are only 17 different shapes for all submirrors. It means only 17 molds with different types are needed. By using stressed-mirror method to figure these molds with annular polishing machine should be easier than to figure hexagonal one.

According to formula (4) and (5) on a submirror the sag can be calculated. When submirror is at the most outer ring of primary mirror the difference of sags in two main directions is maximum which equals 45 µm. We think it is no problem to fabricate these submirrors. It is clear that submirror's displacement along circular direction has no influence for the surface shape of the primary mirror. By using formulae (7) and (8) the surface error caused by the displacement along radial direction of submirror can be calculated. When submirror is at the most outer ring of primary mirror the influence is most sensitive: 4.0 mm displacement along radial direction will produce primary mirror surface error 50nm (at the edge of diagonal of submirror). By using formulae (5) the surface error caused by the rotation around submirror itself can be calculated. Also when submirror is at the most outer ring of primary mirror the influence is most sensitive: 1.8 arcmin rotations around itself will produce primary mirror surface error 50nm (at the edge of diagonal of submirror). These tolerances are rather serious. The compensative mechanism of the primary mirror support structure seems necessary for the zenith distance change and the annual temperature change.

The other three freedoms of each submirror (tip, tilt and piston) should be controlled accurately like all co-phase segmented primary mirrors. It is clear that for such a primary mirror (Fig.9) even all edges of submirrors are co-phase, the petal opening and closing freedom for each ring of submirror can not be controlled i.e. the intersection angle of two rings can not be controlled. We think there are two methods could solve this problem. One is installing two zero-expansion glass bars on the backs of two submirrors A and B (Fig.10), which are at two adjacent rings, and the third bar is installed at the primary mirror cell. There are four pairs of displacement sensors installed on these bars. According to four readings of displacement sensors the intersection angle of two rings can be known. Another method is to use Shack-Hartmann test in real-time during observation to test and control the closing and opening freedom for each ring. Besides above problem, see Fig.9, it is apparent that at all edges of two adjacent rings the distribution of displacement sensors are not equally. What is the influence of it on the accuracy of co-phase? We have not researched yet. So until now we have not finally decided partial annular submirror will be used or not.

4. SOME CONSIDERATIONS ON ADAPTIVE OPTICS IN THIS TELESCOPE

(1) There will be many adaptive optical systems in such a large telescope. These systems work on different wavebands. The different optical components should be used. The deformable mirrors of them have different work frequency in space and time and with different requirement of accuracy. The atmospheric dispersion should be corrected with different waveband and requirement. Some adaptive optics systems are Multi-Conjugated Adaptive Optics systems which use several deformation mirrors vs. different height of layers of atmosphere. Telescope should give an excellent image quality and provides a convenient position with enough area. Most adaptive optical systems are installed after the telescope foci.

(2) If possible, some telescope components should be also used as adaptive optics components. In this configuration if two set first planar mirrors are used (one for Nasmyth I and II and another for coude system), the first one can be used ideally as a tip-tilt mirror for Nasmyth I and II. Since the size of second one is too big it is difficult to be used

as a tip-tilt mirror. In this situation may be a planar mirror in the following optical system of coude system can be used as a tip-tilt mirror for coude system.

(3) In CFGT if a planar mirror is used as a tip-tilt mirror like in above, the secondary mirror could be made as a deformable mirror of adaptive optics.

(4) In CFGT all secondary mirrors can be used as tip-tilt mirror. But in this situation a malalignment coma will be led[18]. Since such a coma is much less than the sky correcting angle of tip-tilt in some situations it is unnecessary to be corrected. But in diffraction-limited observation such a coma should be corrected. According to the amount and orientation of rotation angle of secondary mirror the wave coma can be calculated and can be corrected by deformable mirror[18]. But anyway this increase the complex and lead some error. Another method is to use the free-coma tip-tilt secondary mirror[18-19]. It seems a good option but realizing such a movement is difficult.

5. TELESCOPE MOUNTING AND STRUCTURE

An alt-azimuth mounting is adopted for CFGT (Fig.12). In order to avoid adding much counterweight the horizontal axis is taken on the front of primary mirror. A special rocking chair structure, which is designed by Guoping Li[20], realizes such a requirement successfully. This mechanism also realizes four big Nasmyth platforms. From the side view of CFGT, it looks like a bulb of an electric lamp that makes the configuration to form a compact structure for such a huge telescope. The whole optical system is supported on two parallel rails which are held by 16 oil pads (8 on each rail). The special arrangement for CFGT is that four Nasmyth platforms with two on each side to let following optical systems, adaptive optical systems and focal instruments to be located on the places where the gravitational load direction are unchangeable. In our configuration Nasmyth II platform can be rotated round the vertical principal ray, which from second planar mirror, thus the rotation of field of view can be compensated for all instruments on this platform at the same time. The coude focus is located underground, where the huge instruments could be installed and it could be arranged specially for the futute usage in the long baseline stellar interferometer.

The whole dimension of the structure is about 55m high, 70m x 40m in width, the altitude axis is 3 m above the vertex of the primary mirror and about 30m bellow the vertex of the secondary mirror. One can see the length of the telescope tube in 33m is not very long. Because the size of the secondary mirror is small (about 2.5m), the telescope tube could be formed by four structured legs fixed on two rails of the rocking chair to hold the secondary mirror cell. To change the optical system to the wide field of view system, two mirrors, a pair of lens-prisms and optical fibre positioning system have to be added. By exchanging the above part of tube two secondary mirrors and the wide FOV system can be moved on or moved off.

Due to the secondary mirror system is small and the tube is not very heavy, the structure behind the primary mirror could be light also, but it should be with enough stiffness to keep the surface shape of the primary mirror. Obviously, the part below the altitude axis is much heavier than the upper part. In this case like the alt-azimuth mounting of the Schmidt plate in LAMOST, one could take a special mechanism to balancing the load on the altitude axis. The oil pads will be used in azimuth axis also to carry the huge load of the rotational part of the telescope, and define the position of the axis accurately. The direct driving system will be used for altitude axis and also for azimuth axis by several evenly distributed motors.

To get an accurate mirror surface, besides actively and accurately control three displacement actuators to correct the tip, tilt and piston of each submirror, an adaptive structure is needed to compensate the structure deformation on the frame of primary mirror to keep the other two freedoms of each submirror: the movement along the radial direction and rotation around itself in the tolerant range, or these two extra movements could be added in the support system of each sub-mirror to be controlled actively. A kind of such support system with a parallelogram mechanism has been considered and is going to be tested in the near future. The connection between the primary mirror and the main beam of the rocking chair in Fig 12 is going to be modified futher also.

6. RELEVANT FORMULAE

See Fig.11

(1) The surface shape of rotating conic surface is

$$x^2 + y^2 - 2rz + (k+1)z^2 = 0 \tag{1}$$

The section of it is

$$x^2 - 2rz + (k+1)z^2 = 0 \tag{2}$$

r is the radius of curvature at the vertex. k is the conic constant.

(2) Taking rotating conic surface as the surface of a two-mirror system, according to eliminating third-order spherical aberration and coma, the conic constants of two surfaces equal

$$\begin{cases} k_1 = \dfrac{2(1-\frac{mb}{f})}{m^3(1-\frac{b}{f})} - 1 \\ k_2 = -\dfrac{(m-1)[m^2(1-\frac{b}{f})+1+\frac{b}{f}]}{(m+1)^3(1-\frac{b}{f})} \end{cases} \tag{3}$$

f is the focal length of this two-mirror system. m is the magnification of the secondary mirror. b is the distance from the vertex of primary mirror to final focus (ignoring the planar mirror). In our paper f>0, m<0, b>0.

(3) At point A two main radii of curvature of a rotating conic surface are

$$\begin{cases} r_1 = \dfrac{(r^2 - k\rho^2)^{\frac{3}{2}}}{r^2} \\ r_2 = (r^2 - k\rho^2)^{\frac{1}{2}} \end{cases} \tag{4}$$

r_1 is in the plane which is including A and the rotating axis oz. ρ is the distance from A to the rotating axis oz.

(4) The local surface shape (in this paper it means a submirror) until quadratic term is

$$z_1 = \frac{x_1^2}{2r_1} + \frac{y_1^2}{2r_2} \tag{5}$$

Ax_1y_1 is the tangential plane of rotating conic surface at point A. Ax_1-axis and Az_1-axis are in the plane which including A and the the rotating axis oz.

(5) The relationship between Δr_1, Δr_2 and Δk

$$\begin{cases} \Delta r_1 = \dfrac{\partial r_1}{\partial k}\Delta k = -\dfrac{3\rho^2}{2r^2}(r^2 - k\rho^2)^{\frac{1}{2}}\Delta k \cong -\dfrac{3\rho^2}{2r}\Delta k \\ \Delta r_2 = \dfrac{\partial r_2}{\partial k}\Delta k = -\dfrac{\rho^2}{2}(r^2 - k\rho^2)^{-\frac{1}{2}}\Delta k \cong -\dfrac{\rho^2}{2r}\Delta k \end{cases} \tag{6}$$

(6) The relationship between Δr_1, Δr_2 and $\Delta \rho$

$$\begin{cases} \Delta r_1 = \dfrac{\partial r_1}{\partial \rho}\Delta \rho = -\dfrac{3k\rho}{r^2}(r^2 - k\rho^2)^{\frac{1}{2}}\Delta \rho \cong -\dfrac{3k\rho}{r}\Delta \rho \\ \Delta r_2 = \dfrac{\partial r_2}{\partial \rho}\Delta \rho = -k\rho(r^2 - k\rho^2)^{-\frac{1}{2}}\Delta \rho \cong -\dfrac{k\rho}{r}\Delta \rho \end{cases} \tag{7}$$

(7) The relationship between the sag change and Δr_1, Δr_2

$$\Delta z_1 = -\frac{x_1^2}{2r_1^2}\Delta r_1 - \frac{y_1^2}{2r_2^2}\Delta r_2 \cong -\frac{1}{2r^2}(x_1^2\Delta r_1 + y_1^2\Delta r_2) \tag{8}$$

Considering a future large telescope configuration for China is a very hard and important work. We have taken two steps in references 4, 5. We can not say this is the final configuration but we take a new step towards this goal.

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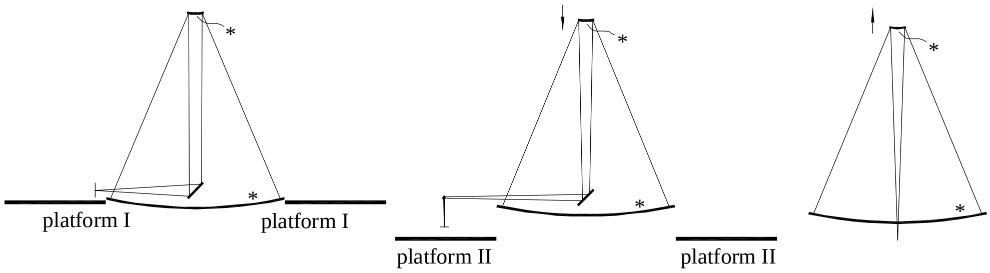


(a) Nasmyth I (b) Nasmyth II (c) Cassegrain

Fig. 1 Optical systems of Nasmyth I, Nasmyth II and Cassegrain

(all systems are R-C systems with one secondary, * conic curved surface)

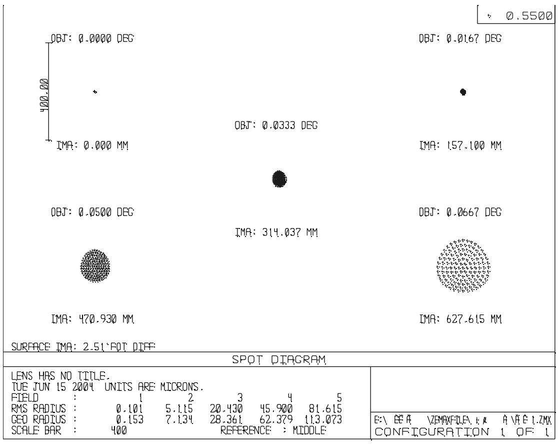


Fig. 2 Spot diagram of Nasmyth I

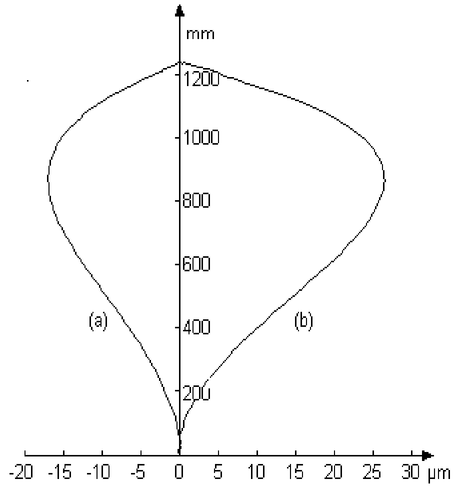
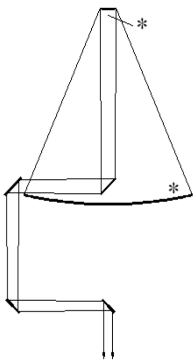


Fig. 3 Curve of surface shape difference of secondary mirrors

(a) difference between Nas. I and Nas.II

(b) difference between Nas. I and Cas.



to focus

* conic curve surface

Fig. 4 Coude system

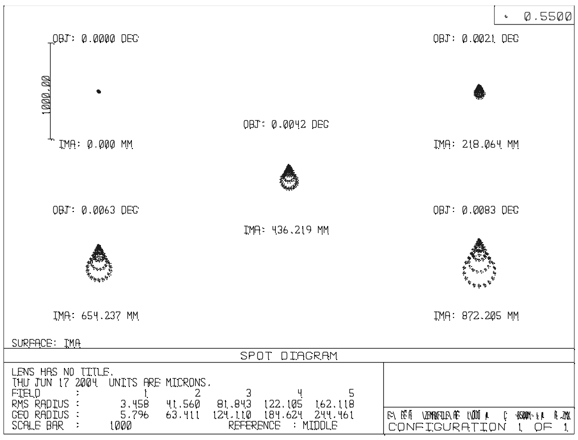
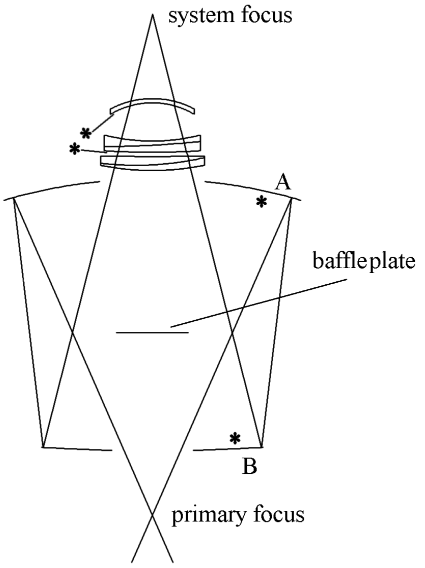


Fig. 5 Spot diagram of coude system



*aspherical surface

Fig. 6 Wide FOV system (exclude primary mirror)

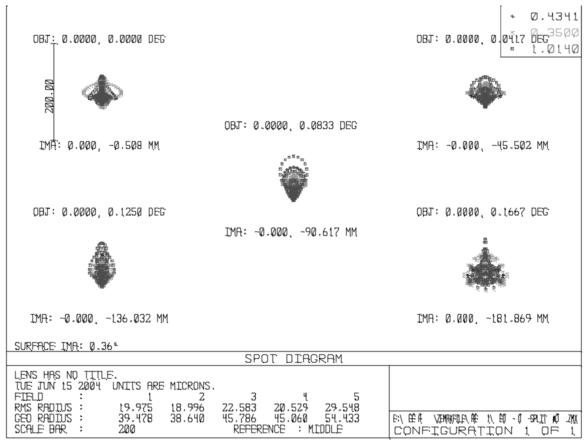


Fig. 7 Spot diagram of Wide FOV system at z=0°

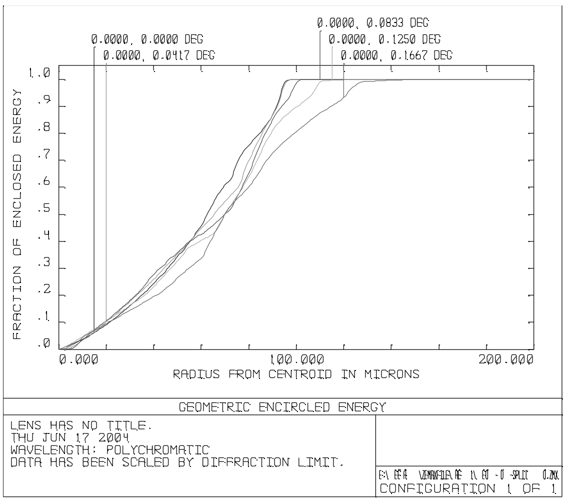


Fig.8 Geometric encircled energy of wide FOV system at z=70°

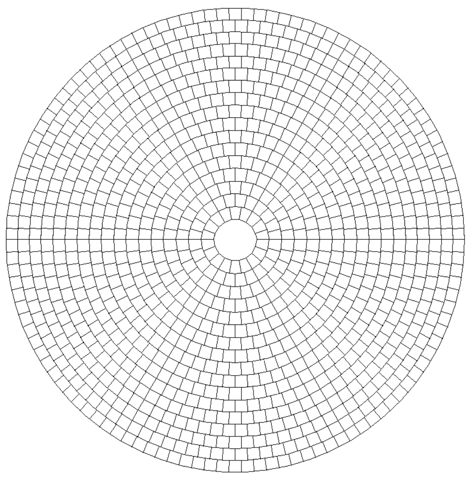
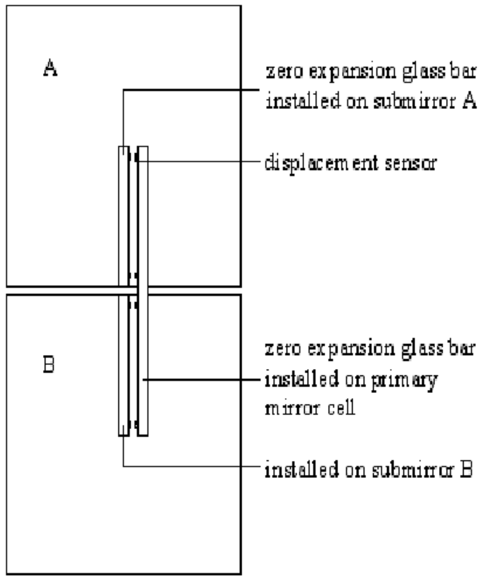


Fig.9 Segmented primary mirror



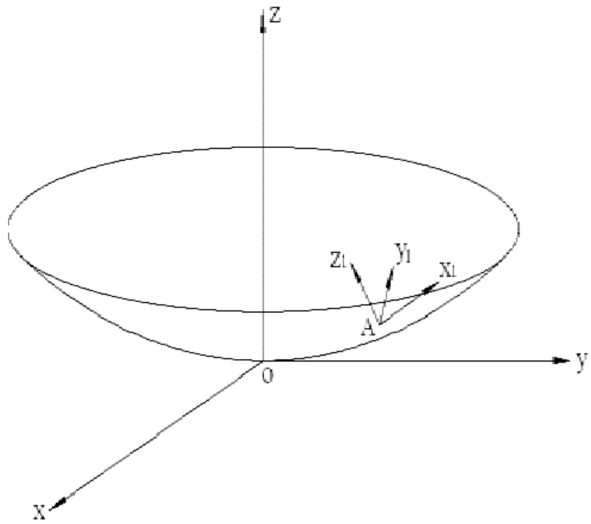


Fig.10 Measurement principle of angle between two rings of primary mirror

Fig. 11 A rotating conic surface

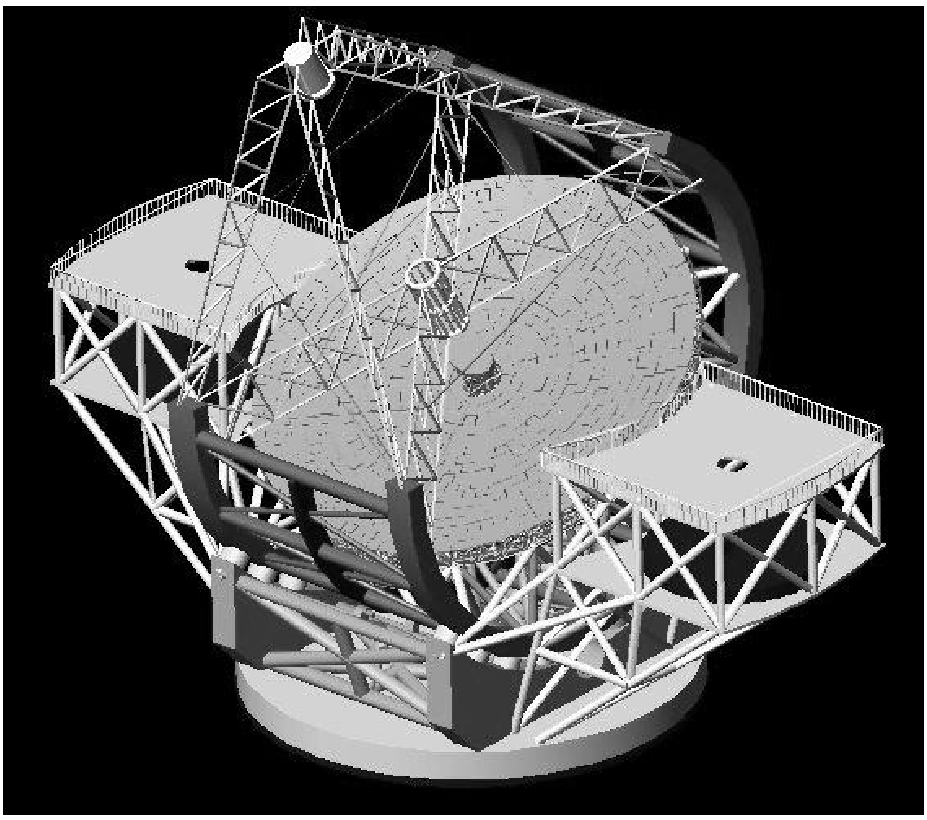


Fig. 12 Telescope mounting