# Field Scanner Design for MUSTANG of the Green Bank Telescope

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**ABSTRACT**

MUSTANG is a bolometer camera for the Green Bank Telescope working at frequency of 90 GHz. The detector has about half arcmin field of view. To cancel out random emission change from atmosphere and other sources, it requires a fast scanning reflector system of few arcmin ranges. In this paper, aberrations of an optimized off-axis system, such as that used in GBT, are briefly discussed. However, as image transfer mirrors are introduced, the new system will have larger aberrations of off-axis system. In this paper, different scanning mirror arrangements are analyzed using ray tracing tool, including scanning with subreflector, chopping a flat mirror and transferring image with an ellipse mirror, and chopping a flat mirror and transferring image with a pair of face-to-face paraboloid mirrors. System analysis shows that chopping a flat mirror and using a well aligned pair of paraboloids can satisfy the field of view requirements of the MUSTUNG system, while other systems all suffer from larger off-axis aberrations. The spread of the spot diagrams of the well aligned pair of paraboloids is only about one Airy disk size within a scanning angle of about 3 arcmins.

**Keywords:** antenna, optics, off-axis, linear astigmatism, coma, reflector scanner, corrector.

## 1. Introduction

MUSTANG (Multiplex SQUID TES Array at Ninety GHz) is a 90 GHz bolometer large focal plane array with 64 detector units specially designed for the Green Bank Telescope (GBT) (Jewell and Prestage, 2004). Equipped with extremely sensitive transit edge sensors (TES) and Superconductor Quantum Interference Devices (SQUIDs), MUSTANG forms diffraction limited image at 90 GHz frequency and is suitable for a wide range of astronomical observations. With its limited 32 arcsecond field of view, to cancel out systematic noises from atmosphere or electronics requires a fast scanning/chopping device over a 3 arcmin range. From the chopping or scanning process, noises common to many pixels are eliminated while signals are extracted with no loss in efficiency.

GBT is an optimized off-axis optical system. By either chopping subreflector away from its idea position or adding image transferring mirrors in the system, the optimized off-axis system may be destroyed with added system aberrations. In most cases, it produces ugly beams or images with strong linear astigmatism and coma. At the same time, since the pulse tube operation of the MUSTANG cooling system has limited angular range requirement, moving MUSTANG device out from GBT Gregorian focus turret and mounting it in a fixed location would yield significant cryogenic operation improvement of the receiver. For these two reasons, a well-behaved chopping mirror and an optimized imaging transferring system is urgently required to allow MUSTUNG device's fast scanning over a larger field angle range.

The aberration and polarization issues of an off-axis optical system are well discussed by Mizugutch (1976), Dragone (1982), Rusch et al (1990), Noethe et al (2000), Chang et al (2005), Chang (2006), and Cheng et al (2010). To avoid unacceptable linear astigmatism and polarization, certain conditions have to meet for an optimized off-axis system. Otherwise, an off-axis optical system may have a zero field of view which only allows observation at a single point position. This required condition is possible only for a two-mirror system, not a one-mirror one. This brings difficulties in the MUSTANG chopping device design. In this paper, ray tracing examples of subreflector chopping and of flat mirror choppers with different image transferring systems are presented. In the end, a flat mirror chopper with a well aligned coma-free Czeny-Turner arrangement of two face-to-face paraboloid reflectors is presented. The focal plane of the paraboloid mirror is nearly parallel to the GBT focal plane. Therefore, the image degradation is minimum and the image quality meets the fast scanning requirement.

## 2. Field of view for optimized off-axis optical systems

For axial symmetric optical systems, major aberrations include spherical aberration, linear coma, and quadratic astigmatism. When components shift away from their positions, pointing change, constant coma, and linear astigmatism will be produced. The constant coma fills all field of view and it can only be canceled by shifting another component in the system. This produces an off-axis system free from constant coma, but not other aberrations. Generally, constant coma and linear astigmatism exist in off-axis optical systems. Off-axis focus system may only have zero field of view.

Inside an off-axis system, linear astigmatism and cross polarization are produced as off-axis tangential rays focus at a position different from that of the off-axis sagittal rays. However, if certain conditions are met in an off-axis system (Dragone, 1982), both linear astigmatism and cross polarization disappear. The dominant aberration is linear coma in an optimized off-axis system. The GBT optics is an optimized one. At its Gregorian focus, there is no linear astigmatism. The dominant aberration is linear coma. The ray tracing spot diagrams over a 4 arcmins field of view is shown in Figure 1. In the figure, from left to right and from top to bottom, the image spots are at (0,0), (0, 2 arcmin), (0,4 arcmin), (0, -2 arcmin), (0,-4 arcmin), (-2 arcmin, 0), (-4 arcmin, 0), (2 arcmin, 0), and (4 arcmin,0) positions respectively. The circle diameter is 7.72 mm, the size of the Airy disk at 90 GHz.

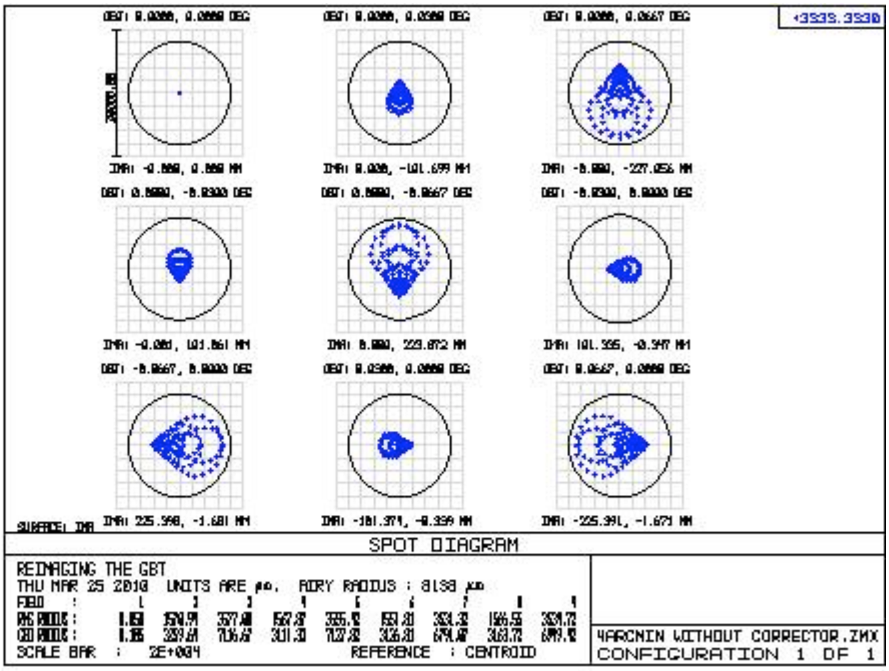


Figure 1. Ray tracing results of the GBT optics within a 4 arcmins field of view. The circles are GBT Airy disk at 90 GHz.

## 3. Scanning system design for the GBT optics

For axial symmetric telescopes, scanning a small area of sky can easily be realized by either moving the whole telescope or chopping the subreflector mirror. Unfortunately, with its heavy and huge structure, moving the whole telescope is extremely slow. Efforts had been taken in chopping the subreflector mirror of the GBT. As discussed earlier, any movement of its subreflector mirror results in a distorted focusing system, so that ugly beam is formed in the focus point. When the subreflector tilts 0.12 degrees and the beam moves 1 arcmin on the sky, the Strehl ratio of the system drops quickly to 0.5. The image spread on the MUSTANG receiver increased from about 8”×8” in the focal center (telescope focal point) to about 15”×15” at 1 arcmin away from the field center (Mason, 2008). Figure 2 shows the beam shape change in one direction by using the subreflector scanning from the focal center to 1 arcmin away from the center (Dicker, 2008). The beam has a strong asymmetric, ellipse shape as the linear astigmatism dominants this distorted focusing system.

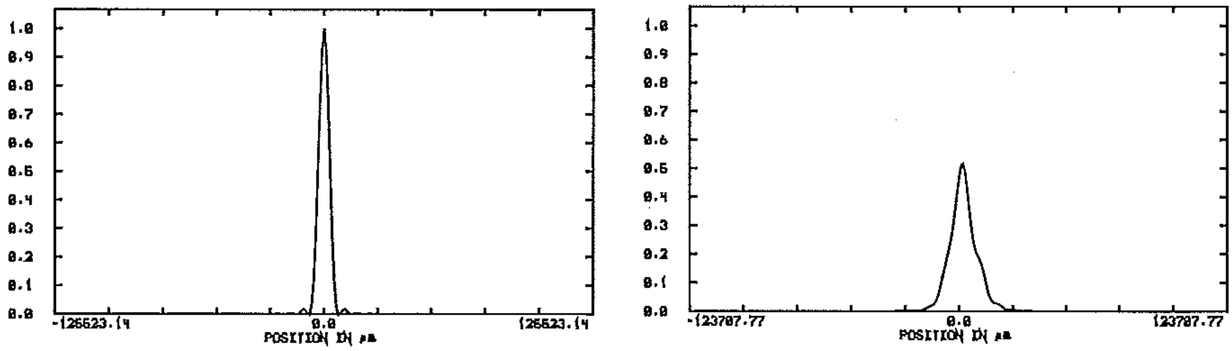


Figure 2: Beam pattern changes using subreflector scanning from focal center (left) to 1 arcmin away from center (Dicker, 2008)

The alternative way to scan the sky is to insert a flat mirror with its axis slightly away from the mirror surface normal. When the mirror rotates around this axis, the beam will move back and forth about two positions in the sky. Normally, an image transfer system is required for the system. The simplest image transfer is using an ellipse mirror. It can transfer an image perfectly from one of its focii to another. However, the added surface is another off-axis system which does not satisfy the linear astigmatism free condition. Figure 3 shows both the proposed chopping flat mirror and the ellipse mirror around the focal position of the GBT. Figure 4 is the ray tracing spot diagrams in the focal center and about 3 arcmins away from it. From the left diagrams of Figure 4, the image is perfect over a field of view of 23 arcsecs in the focal center. From left to right and top to bottom the spot diagrams are for (0,0.0064 deg), (0.0064 deg, 0), (0,0), (-0.0064 deg, 0), and (0,-0.0064 deg) field angles. However, when the sky is 3 arcmins away from the center, the image quality is very poor with strong inherited linear astigmatism covering few Airy disk areas. In the right diagrams of Figure 4, the spot diagrams from left to right and top to bottom are for (0,-0.0436 deg), (0.0064 deg, -0.05 deg), (0,-0.05 deg), (-0.0064 deg, -0.05 deg), and (0,-0.0564 deg) field angles.

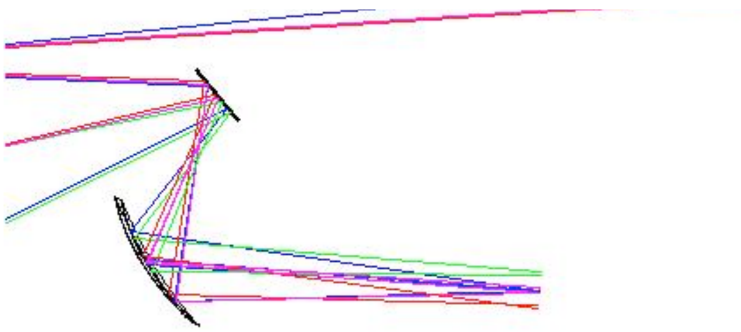

Figure 3. Optical arrangement using a flat chopper and an ellipse reflector mirror.

By adding two curved mirrors in the image transferring system, the linear astigmatism free conditions may be satisfied. Therefore, both the GBT optics and the added system are optimized off-axis systems. Following this approach, a Czeny-Turner arrangement of two face-to-face paraboloid reflectors can be used. These two proboloids have the same f-ratio and they form a coma-free, linear astigmatism free, optimized off-axis system. Figure 5 is such an arrangement. From the figure, it can be found that the focal plane of the added image transferring system has a larger tilting angle relative to the focal plane of the original GBT system. Figure 6 shows the spot diagrams of the system around the focal center and 3 arcmins away from the focal center. From the left diagrams of Figure 6, the image is perfect only in the focal center. The rest images are larger than the Airy disk. From left to right and top to bottom the spot diagrams are for

(0,-0.0064 deg), (-0.0064 deg, 0), (0,0), (0.0064 deg, 0), and (0,0.0064 deg) field angles. When the sky is 3 arcmins away from the center, the image quality is even poor with strong inherited linear astigmatism covering many Airy disk areas. In the right diagrams of Figure 6, the spot diagrams from left to right and top to bottom are for (0,-0.0436 deg), (0.0064 deg, -0.05 deg), (0,-0.05 deg), (-0.0064 deg, -0.05 deg), and (0,-0.0564 deg) field angles. The transferring of the GBT image field is poor because the focal plane is tilt towards the focal plane of the GBT telescope. The GBT images are never well focused in the added image transferring optical system.

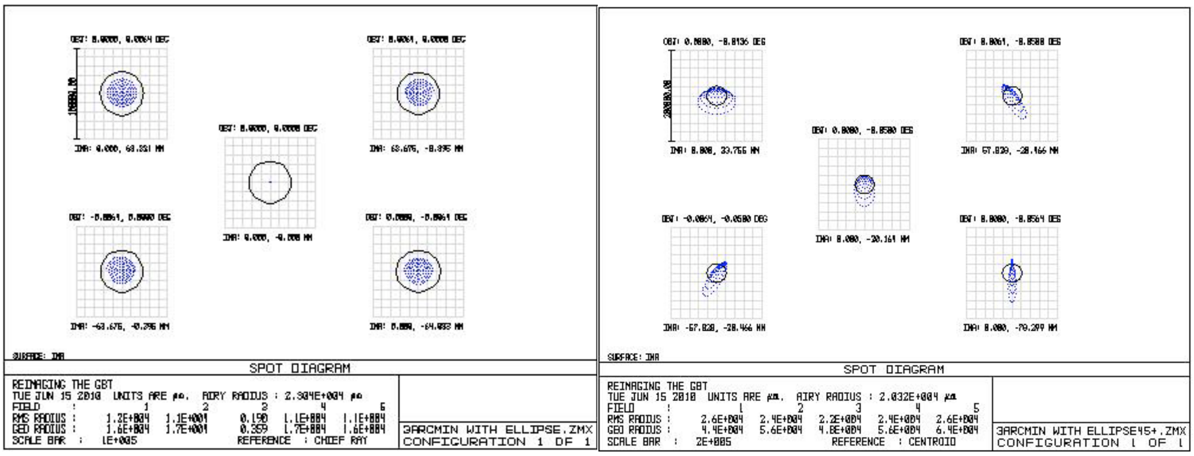


Figure 4. Spot diagrams of a 23" field of view in the focal canter (left) and that of 3 arcmins away from the center (right). The circles are GBT Airy disk at 90 GHz.

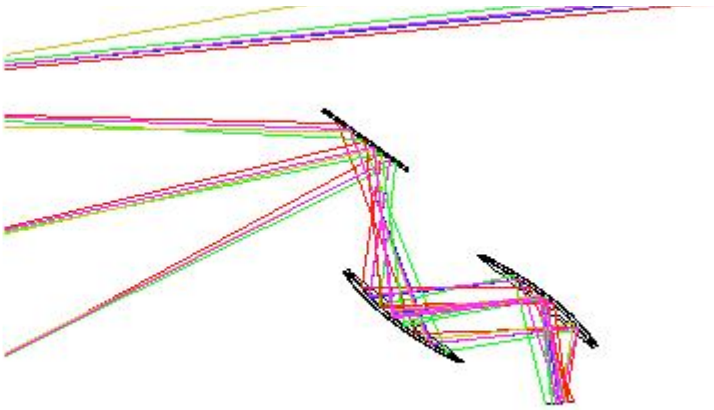

Figure 5. Optical arrangement using a flat chopper and two face-to-face poorly-aligned paraboloid reflectors.

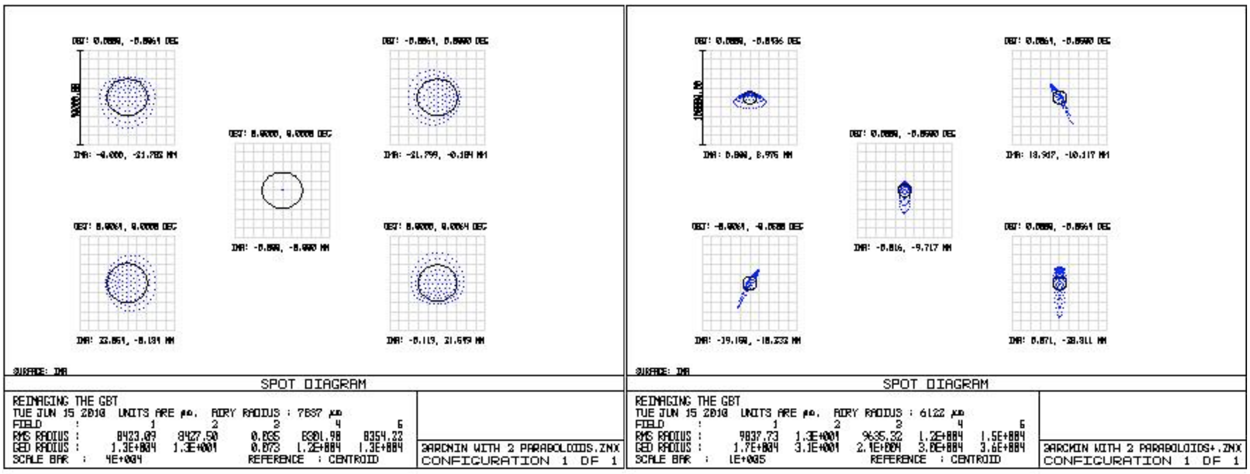


Figure 6. The spot diagrams of a 23" field of view in the focal canter (left) and that of 3 arcmins away from the center. The circles are GBT Airy disk at 90 GHz.

From the above discussion, the added image transferring system should be well-aligned with the focal plane of the GBT system. Figure 7 shows this improved flat chopper and the added image transferring system with two face-to –face, coma free, linea astigmatism free paraboloids with their focal plane nearly parallel to the focal plane of the GBT optics. The imaging results are greatly improved. In Figure 7, the Y-Z plane is shown on the paper surface with Y in the right hand direction and Z in the downward direction. This design may be used as the GBT Mustang chopping system. The details of the mirror parameters of this system are all listed in Table 1.

The flied scanning is done through the rotation of the flat chopper in Y direction. When the flat mirror tilts about 2.6 degrees about Y direction, the scanned field angle is 3 arcmins in the negative X direction. In the left side of Figure 8, the spot diagrams are at field angle (-0.0083 deg, 0); (0,-0.0083 deg); (0,0); (0.0083 deg, 0); and (0, 0.0083 deg). The spot diagrams 3 arcmin away from the focal center are shown in the right of Figure 8. The spot diagrams are at the field angle of (-0.0583 deg, 0); (-0.05 deg, -0.0083 deg); (-0.05 deg, 0); (-0.05 deg, 0.0083 deg); and (-0.0417 deg, 0). When the scanner is 3 arcmin away from the focal center, the rms spot radii with the MUSTANG device are 4.6 mm, 4.7 mm, 3.0 mm, 4.9 mm, and 4.7 mm respectively. These numbers are well below Airy disk size of 7.72 mm. During the chopping, the detector remains stationary at its fixed position. In this design the distance between two paraboloids can be adjusted without effect on the image quality. This design can be used at the GBT focus to meet the image quality requirement in the MUSTANG Chopping observation.

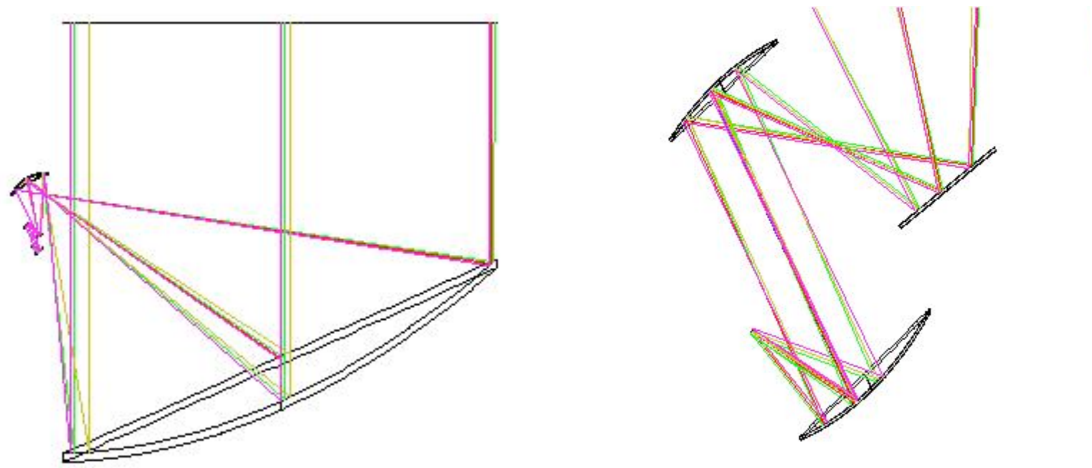

Figure 7. Optical arrangement using a flat mirror chopper and two face-to-face well-aligned paraboloid reflectors. The

flat mirror can scan 3 arcmins through the rotation about an axis with a small angle to the mirror surface normal.

Table 1 Position and parameter details of the scanner system.

| | Flat scan mirror | Paraboloid 1 | Paraboloid 2 | Final focus |
|---|---|---|---|---|
| Distance to previous surface | 1916 mm (to GBT focus) | 3416 mm | 3000 mm or larger (This may change) | 1500 mm |
| Diameter | 1000 mm | 1000 mm | 1000 mm | |
| Focal length | | 2000 mm | 2000 mm | |
| Tilt about X | -45 deg | 42 deg | 42 deg | |
| Decenter about Y | | | -2650 mm | |

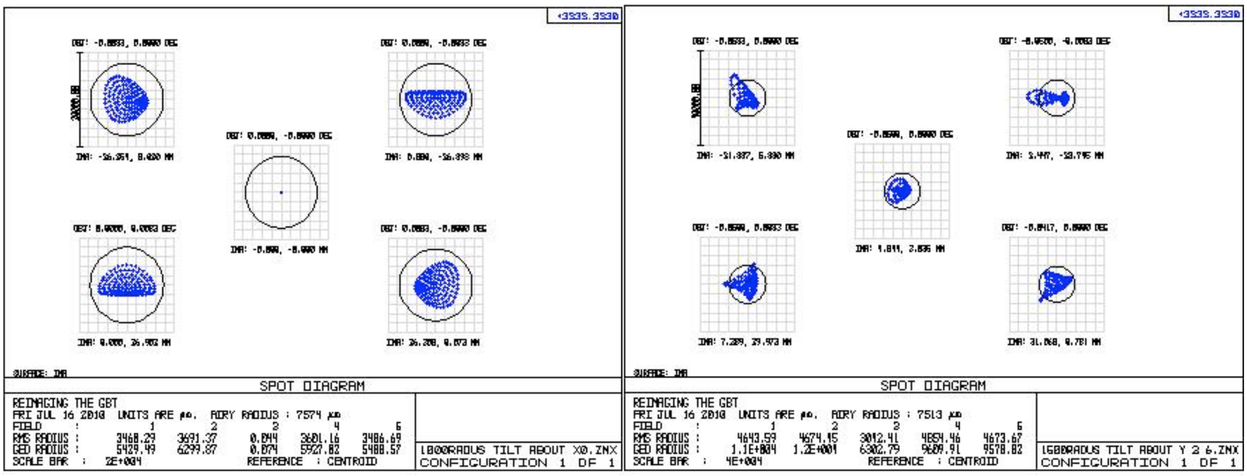


Figure 8. The spot diagrams of a 30" field of view in the focal canter (left) and that of 3 arcmins away from the center. The circles are Airy disk at 90 GHz for two well-aligned paraboloid reflector system.

## 4. Discussions and conclusions

Adding imaging transferring optics into or changing existing optimized off-axis system are difficult tasks as the new systems produced may have extremely small field of view. In this paper different schemes for scanning a small angular range of sky for the GBT are explored. Much attention was paid in retaining the image quality in the original GBT focal field. Finally, a field scanner with up to 3 arcmins field of view for GBT is successfully designed which meets the image quality requirements of the MUSTANG device. In this design, the image transferring system is a pair of face-to-face paraboloidals, a classical coma free optimized off-axis optical system. The added system added litter in the final image aberrations. By rotating the flat mirror with a tilting angle of about 1.3 degrees in Y direction, the system can quickly scan 3 arcmin sky areas. The rms spot size at the 3 arcmin field angle is only a little more than 4 mm in diameter.

As this paper is still in preparation, a new MUSTANG II device with much more pixels is near its completion stage. The new device has a larger field of view, about 1 arcmin in radius. The above designed system may not meet the requirement of the MUSTANG II device. To design a suitable scanner for the MUSTANG II device requires further optimization work. More attention has to be paid in reducing coma aberration which is inherited in the GBT off-axis optical system. Ming Liang provided help and advice in this work.

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