RAA 2020 Vol. **20** No. **1**, 1(5pp) doi: 10.1088/1674–4527/20/1/1

http://www.raa-journal.org *http://iopscience.iop.org/raa*

Research in Astronomy and Astrophysics

LETTERS

Suggested quasi-Cassegrain system for multi-beam observation of FAST

Ding-Qiang Su (苏定强)[1,2], Hua Bai (白华)[2] and Xiang-Qun Cui (崔向群)[2]

[1] School of Astronomy and Space Science & Key Laboratory of the Ministry of Education, Nanjing University, Nanjing 210023 , China; *dqsu@nju.edu.cn*

[2] National Astronomical Observatories/Nanjing Institute of Astronomical Optics and Technology (NIAOT), Chinese Academy of Science, Nanjing 210042, China

Received 2019 September 20; accepted 2019 October 29

Abstract FAST, the largest single-dish radio telescope in the world, has a 500-meter diameter main reflector and a 300-meter diameter illuminated area. It has a main reflector that can vary its shape, which continuously changes the shape of the illuminated area in reflector into a paraboloid. In this article, we propose a quasi-Cassegrain system for FAST. The detailed design results are provided. Such a quasi-Cassegrain system only needs to add a 14.6-meter diameter secondary reflector, which is close to the size of the feed cabin. The distance from the secondary reflector to the focus is only 5.08 m, and it has excellent image quality. In this quasi-Cassegrain system, the shape of the illuminated area in the main reflector continuously changes into an optimized hyperboloid. Using this quasi-Cassegrain system from frequency 0.5 GHz to 8 GHz, the multi-beam system can include 7 to 217 feeds. If this system is used in combination with Phased Array Feed (PAF) technology, more multi-beam feeds or a higher working frequency can be used.

Key words: telescope — techniques: miscellaneous — methods: miscellaneous — instrumentation: miscellaneous — surveys

1 INTRODUCTION

The Five-hundred-meter Aperture Spherical radio Telescope (FAST)[1] (Peng et al. 2009; Nan et al. 2017; Jiang et al. 2019) is a Chinese national large scientific engineering project and the largest single-dish radio telescope in the world. Active optics technology (Wilson 1999; Lemaitre 2009), which was developed in the 1980s and is applied for correcting gravitational deformation and thermal deformation in large telescopes (LTs), keeps the large mirrors of telescopes in an accurate shape and collimation. In 1986, Ding-qiang Su put forward the idea of “shape variable mirrors” (Su, Cao & Liang 1986), using active optics technology to produce some optical systems which could not be realized traditionally. This opened up a new direction for active optics. In that paper, one of the two examples is as follows:

“*Like Arecibo 305-meter radio telescope, a very large optical telescope, as proposed by a few people, could use a fixed or half fixed spherical primary mirror and let the secondary or corrector do tracking movement near the primary focal plane. In these configurations the continuous fields of view are very small due to the considerable off-axis aberrations. If we use the method described in this paper, i.e., continuously changing the shape in the area in use on the primary to make it maintain the optimum shape, e.g. paraboloid or hyperboloid, consequently the best correction could be obtained in large continuous field.*”

Although the above idea was proposed for optical systems, since optical systems and radio systems tend to borrow concepts from each other, the above idea also can be applied to radio systems. In 1998, Yuhai Qiu (Qiu 1998a,b), one of the main members of FAST, proposed to continuously change the shape of the illuminated area in the 500 m main reflector into a paraboloid, i.e., the same idea as that in our paper (Su, Cao & Liang 1986). Bo Peng, a main member of FAST, actively supported this innovation. Finally, this idea was adopted for FAST. This is the most significant difference between FAST and Arecibo,

[1] `http://fast.bao.ac.cn.`

and is the key innovation in FAST. The "shape variable mirrors" idea is also the key innovation in LAMOST, another Chinese national large scientific engineering project and the largest wide field of view combining large aperture optical telescope in the world[2] (Wang et al. 1996; Cui et al. 2012). In this article, we propose to add a quasi-Cassegrain system for FAST. The detailed process of design and associated results are given in the following.

2 A BRIEF INTRODUCTION TO FAST

In 1993, an international astronomical community (composed of 10 countries including China) proposed to develop a next-generation LT for radio astronomy. As part of the LT scheme, in 1994 some Chinese astronomers proposed to develop a radio telescope similar to Arecibo[3] , with a spherical main reflector, a 500 m aperture and a 300 m diameter illuminated area. Since the shape of Arecibo's main reflector is spherical, it has serious spherical aberration. If a corrector is added to eliminate spherical aberration, the FOV is still very small due to considerable off-axis aberrations. If the f-ratio (the focal length divided by the diameter of the illuminated area in the main reflector) is increased, these aberrations can be decreased, but the observable sky range will lessen as well. In Arecibo, the diameter of the main reflector is 305 m, the diameter of the illuminated area is 221 m, the radius of curvature for the main reflector is 265 m and the f-ratio is 0.600. See Section 1 of this paper for the "shape variable mirrors" idea (Su, Cao & Liang 1986), i.e., continuously changing the shape in the illuminated area on the main reflector to make it maintain a paraboloid, so that the spherical aberration is eliminated completely. Since the illuminated area in the main reflector of FAST is paraboloid, it has no spherical aberration, therefore it can acquire observations without any corrector. In FAST, the f-ratio is 0.4611. Thus, FAST can observe a much larger sky range than Arecibo, which is another important advantage. The first light of FAST was on 2016 September 25, and now it is in the commissioning stage. Australian astronomers are helping the FAST team to develop multi-beam feeds. A 19-beam feed, developed in Australia, has been installed and has started to work at the FAST paraboloid prime focus. Until 2019 June 10, 100 new candidates of pulsars have been found using the drift scanning method, and among them 65 have been identified as pulsars. In addition, a pulsar with interesting emission properties was discovered (Zhang et al. 2019). Figure 1 is a photo of FAST.

[2] `http://www.lamost.org`
[3] `http://www.naic.edu.`

3 THE QUASI-CASSEGRAIN SYSTEM FOR FAST

Su pointed out in the above paper (Su, Cao & Liang 1986) that the shape of the illuminated area on the main reflector also can be hyperboloid. This means a secondary reflector is added and can obtain a wide FOV quasi-Cassegrain system for multi-beam observation. Hua Bai designed a series of quasi-Cassegrain systems for FAST, in which secondary reflectors have different magnifications and all of these diameters are near 15 m, i.e., near the diameter of the feed cabin. During the design process, we were clearly aware that this quasi-Cassegrain system is a reflecting system, for which wavelength is irrelevant, and for the FOV, a radius of 0.56 deg was assumed. The coefficients a_4, a_6, a_8, a_{10} of the secondary reflector shape formula in Table 1 and the conic constant cc ($= -e^2$, where e is eccentricity) of the illuminated area in the main reflector are optimized. The ZEMAX software is used for this design. Bai found magnification of the secondary reflector from $1.5 - 2$ is good. As magnification increases, the image quality improves and the linear obstruction ratio is somewhat reduced, but the distance from the vertex of the secondary reflector to the focus is increased. Parameters for the structure of the quasi-Cassegrain system, which we selected, are listed in Table 1 and the design is displayed in Figure 2. The magnification of the secondary reflector is 1.628 and the quasi-Cassegrain system's f-ratio is 0.7507. The shape of the illuminated area is hyperboloid with the conic constant cc (i.e., $= -e^2) = -1.0311329$. The maximum deviation between this hyperboloid and paraboloid is only 1.8 cm in the illuminated area of the main reflector. Since the main reflector is a "shape variable mirror," the exchange between two shapes is easy. The diameter of the secondary reflector is 14.60 m, which is close to the size of the feed cabin. This secondary reflector can be fixed under the feed cabin. In this quasi-Cassegrain system, distance between the vertex of the secondary reflector and the focus is 5.080 m. The multi-beam feeds, when they are at the focus, can be connected to the secondary reflector by blades. The distance between the prime focus (i.e., the paraboloid focus) and the vertex of the secondary reflector is 3.03 m. Values for the root mean square (RMS) wave aberration with GHz frequency and FOV radius *w* are given in Table 2. The unit of the FOV radius *w* is the same as the diameter of the Airy disk for corresponding frequency. Thus, it is easy to see how many feeds can be included for this multi-beam system. For example, in Table 2 if $w = 3$ with frequency $= 1$ GHz (i.e., $\lambda = 30$ cm), RMS wave aberration is 0.0432λ. $w = 3$ means that the FOV radius is three times the diameter of the Airy disk at frequency 1 GHz. If the

Fig. 1 A photo of FAST provided by the FAST team.

feed diameter is taken as the diameter of the Airy disk, 37 multi-beam feeds can be installed. We restrict the diameter of multi-beam feeds to not exceed 4 m. The equivalent linear obstruction ratio (denoted as η) is 0.22. In this situation, the energy loss is only about 5%, and the diffraction distribution has a small deterioration. We stipulate that the image quality RMS wave aberration be less than λ/14 (i.e., $< 0.0714\lambda$) and the linear obstruction ratio be less than 0.22 (i.e., $\eta < 0.22$). In Table 2, all listed values corresponding to linear obstruction ratio $\eta < 0.22$. From Table 2, one can find that for frequency 0.5 GHz and a multi-beam system that includes 7 feeds, $\eta = 0.18$ can be obtained from calculations; for 1 GHz and 37 feeds, $\eta = 0.21$; for 2 GHz and 91 feeds, $\eta = 0.17$; for 4 GHz and 169 feeds, $\eta = 0.11$, and for 8 GHz and 217 feeds, $\eta = 0.064$. All these multi-beam systems satisfy the above two conditions. This quasi-Cassegrain system has excellent image quality, many feeds can be included for multi-beam observation, and it is small and exquisite. We do not think this quasi-Cassegrain system with a secondary reflector is complicated. Since the main reflector of Arecibo is invariably spherical, when the secondary and tertiary reflectors are added, if its illuminated area is the same as ours, the aperture of the secondary reflector is nearly more than two times bigger than ours. At the paraboloid prime focus, coma is serious. The size of coma is proportional to the FOV. The diameter of the Airy disk is proportional to λ. From these considerations, one can find that for the paraboloid prime focus for a certain *w*, the RMS wave aberration has the same coefficient, which is irrelevant to λ. This is also demonstrated by calculation. However, the paraboloid prime focus also has other off-axis aberrations (for example, astigmatism, high-order aberrations, etc.), which are not proportional to FOV, so the above results are approximative. The RMS wave aberration of the FAST paraboloid system is also shown in Table 2.

Phased Array Feed (PAF) is a very important new technology. In the long run, with this technology there will be no requirement for image quality for multi-beam systems, but at the moment, with PAF technology the wave aberration can be greater than λ/14, but not too much more. From Table 2 one can see that for the same *w*, the RMS wave aberration of the quasi-Cassegrain system is much smaller than that of the paraboloid prime focus system, which gives us the idea that by utilizing the quasi-Cassegrain system and PAF technology, a multi-beam system can be obtained which includes more feeds, especially for high frequency. Please note that this article has prescribed linear obstruction ratio η should be less than 0.22. For FAST 0.5 GHz and 1 GHz, if more than 7 and 37 feeds are needed respectively, such multi-beam systems should be installed at the prime focus with PAF technology. For the above quasi-Cassegrain system, if implementing PAF technology for frequency 2 GHz and 127 feeds, $\eta = 0.20$; for 4 GHz and 271 feeds, $\eta = 0.17$; for 8 GHz and 469 feeds, $\eta = 0.094$ may be obtained, and conceivably for 4 GHz and especially for 8 GHz, more feeds can be included by using PAF technology. The working frequency of

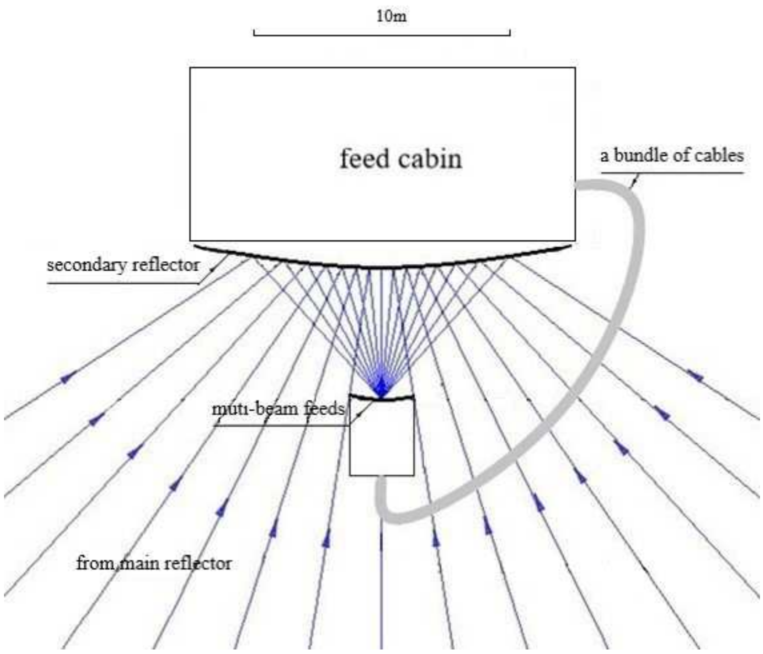

Fig. 2 FAST quasi-Cassegrain system, secondary reflector and multi-beam feeds.

Table 1 Structure of the FAST Quasi-Cassegrain System

Element	Aperture (m)	Vertex radius of curvature (m)	Thickness (m)	Conic constant cc ($= -e^2$)	a_4	a_6	a_8	a_{10}
Main reflector	300	–276.6600	–135.3000	–1.0311329				
Secondary reflector	14.60*	–15.70926	5.080000	0	8.884461E-13	–2.095897E-20	3.004833E-28	–1.707826E-36
Focal surface	4.00	–5.518697						

* corresponding to the diameter of linear FOV 4 m.

$x = (c(y^2+z^2))/(1+\sqrt{(1-c^2(1+cc)(y^2+z^2))}) + a_4(y^2+z^2)^2 + a_6(y^2+z^2)^3 + a_8(y^2+z^2)^4 + a_{10}(y^2+z^2)^5.$

Table 2 RMS Wave Aberration with Frequency and *w* in FAST

Element	Frequency	RMS wave aberration												
		$w=0$	$w=1$	$w=2$	$w=3$	$w=4$	$w=5$	$w=6$	$w=7$	$w=8$	$w=9$	$w=10$	$w=11$	$w=12$
Paraboloid prime system	Any Frequency	0.0033	0.1031	0.2059	0.3088	0.4116	0.5145	0.6174	0.7202	0.8231	0.9259	1.029	1.132	1.234
Cassegrain system	0.5 GHz (λ60 cm)	0.0031	0.0098											
	1 GHz (λ30 cm)	0.0061	0.0089	0.0197	0.0432									
	2 GHz (λ15 cm)	0.0123	0.0136	0.0178	0.0260	0.0393	0.0591	0.0864						
	4 GHz (λ7.5 cm)	0.0245	0.0252	0.0271	0.0306	0.0357	0.0427	0.0519	0.0638	0.0785	0.0967	0.1182	0.1436	
	8 GHz (λ3.75 cm)	0.0490	0.0493	0.0503	0.0520	0.0543	0.0573	0.0612	0.0657	0.0712	0.0778	0.0853	0.0940	0.1039

RMS wave aberration unit is λ. Reference value $\lambda/14 = 0.0714\lambda$. *w* is FOV radius. Unit of *w* is Airy disk diameter of corresponding frequency.

FAST is restricted to about 8 GHz since the shape error of illuminated area in the main reflector is large, but if both PAF technology and quasi-Cassegrain system are applied, the higher working frequency and multi-beam feeds can be used.

4 FEASIBILITY OF THE QUASI-CASSEGRAIN SYSTEM FOR FAST

a. The shape of the secondary reflector is invariant. The diameter of the secondary reflector is only 14.6 m, and the distance to focus is 5.08 m.

b. The minimum working wavelength is about 3.75 cm (8 GHz), so the surface tolerance of the secondary reflector is about RMS 0.5 mm, therefore the secondary reflector is easy to manufacture.

c. The surface shape of the secondary reflector is continuous and smooth.

d. The maximum deviation between the hyperboloid and the paraboloid on the illuminated area of the main reflector is only 1.8 cm, so it is easy to exchange these two shapes.

e. According to our preliminary structure analysis, the weight of the secondary reflector is not more than 10 tons.

f. When the secondary reflector decenters by 5 cm, the mean value of the RMS wave aberration in FOV only increases 8% for any wavelength. When the secondary reflector tilts by 2°, the mean value of the RMS wave aberration in FOV only increases 7% for any wavelength. So, for a given image quality, the tolerances of the secondary reflector are very loose, except that the image position movement caused by decenter and tilt of the secondary reflector needs to be corrected by the auto-guiding system.

According to the above analysis, our suggested quasi-Cassegrain system for FAST is feasible and obviously has low cost.

5 DISCUSSION

a. In this article, the quasi-Cassegrain system has excellent image quality and compact construction. The most important reason for this is the adoption of the "shape variable mirrors" idea proposed by Su in 1986. In real time, the illuminated area is hyperboloid (or paraboloid) rather than an invariable sphere. If the main reflector is an invariable sphere, the results obtained will be far inferior.

b. Some radio telescopes also have a Cassegrain or quasi-Cassegrain system. In general, their focus is fixed and near the vertex of the main reflector, but there is no such fixed focal position near the main reflector in FAST. So, for our quasi-Cassegrain system, the focus must be close to the secondary reflector. In this case, according to our calculation, the image quality is still excellent.

c. One can notice that this quasi-Cassegrain system increases the linear obstruction. However, when magnification is increased, the linear obstruction ratio can be reduced somewhat; when the size of the secondary reflector is increased without changing its magnification, the linear obstruction ratio can be also reduced.

d. The above quasi-Cassegrain system can also serve as a reference for fully steerable radio telescopes with an aperture of several dozen meters to about one hundred meters.

6 CONCLUSIONS

Our suggested quasi-Cassegrain system for FAST is feasible. It is practical for multi-beam observation. Combining PAF technology with this quasi-Cassegrain system for multi-beam observation is also feasible.

Acknowledgements We thank Professors Ron Ekers, Lister Staveley-Smith, Fu Han, Xingwu Zheng and Jinlin Han for their valuable discussion, and Professor Bo Peng's support.

References

Cui, X., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA (Research in Astronomy and Astrophysics), 12, 1197
Jiang, P., Yue, Y. L., Gan, H. Q., et al. 2019, Sci. China-Phys. Mech. Astron., 62, 959502
Lemaitre, G. R. 2009, Astronomical Optics and Elasticity Theory: Active Optics Methods (Springer Berlin Heidelberg)
Nan, R., Zhang, H., Zhang, Y., et al. 2017, ChA&A, 41, 293
Peng, B., Jin, C., Wang, Q., et al. 2009, Proc. IEEE, 1391, 97, 1391
Qiu, Y.-H. 1998a, Acta Astrophys. Sin., 18, 222
Qiu, Y.-H., 1998b, MNRAS, 301, 827
Su, D.-Q., Cao, C.-X., & Liang, M. 1986, Proc. SPIE, 628, 498
Wang, S.-G., Su, D.-Q., Chu, Y.-Q., Cui, X.-Q., Wang, Y.-N. 1996, Applied Optics, 35, 5155
Wilson, R. N. 1999, Reflecting Telescope Optics II (Springer-Verlag Berlin Heidelberg)
Zhang, L., Li, D., Hobbs, G., et al. 2019, ApJ, 877, 55