

Comparison and Demonstration of the Principle and Applications for the State-of-art Astrophysical Telescopes

Binwen Zheng^{*, †}

Britain-China school, Wuhan, China

*The corresponding author's e-mail address: 16011010229@stu.suse.edu.cn

Abstract. With the rapid development of the technique for optics engineering, the telescope has developed rapidly with great performances (i.e., higher resolution), which exhibits great potential in cosmology detection. On this basis, this paper compares and demonstrates the basic principle as well as the state-of-art applications and observations of two typical telescopes, i.e., the Arecibo and Fast. According to the analysis, the later constructed FAST largely expands the searching parameters which offer a path for higher signal-noise ratio. However, it should be noted that ground-based telescopes do have some shortcomings and defects. The revision suggestions are also proposed in order to better upgrade the performances of the telescopes. These results shed light on guiding further exploration of future telescope construction.

Keywords: telescope, apply, Observation status, search argument

1. Introduction

Contemporarily, telescopes play a vital role in astrophysics observation and cosmology diagnostic [1-5]. In general, radio telescope is an important tool for human exploration of the universe, is the main tool to connect the earth and extra-terrestrial bodies. In order to achieve higher performance, radio telescopes are developing towards large aperture and high precision. Due to the influence of non-uniform temperature field, the reflector of radio telescope will produce irregular deformation, which seriously affects the profile accuracy of radio telescope [6-8]. In order to clarify the characteristics of various methods for measuring the surface shape accuracy of large radio telescopes, the methods for measuring the surface shape accuracy of large radio telescopes are divided into four categories: classical measurement, laser measurement, photogrammetry, and microwave holography.

As a matter of fact, the telescopes have a pretty long history. Since Yansky announced the reception of radio signals from the Milky Way, the American G. Reber devoted himself to experiments with radio telescopes and finally succeeded in building one in 1937. Reber is also known as the first creator of the parabolic radio telescope. With the development of the ground telescopes techniques, a large amount of telescopes have been constructed, which achieves a lot of milestones detection results. With this in mind, this paper will discuss and compare two well-known telescopes (i.e., Arecibo and FAST) and demonstrate the current limitations for the telescopes. The rest part of the paper is organized as follows. The Sec. will introduce and review the basic principle of the telescope. Subsequently, the Sec. 3 and Sec. 4 will describe and present the features and parameters for Arecibo and FAST, respectively. Afterwards, the comparison of the two telescopes will be presented in Sec. 5 and the current limitations as well as future outlooks for the telescopes will be proposed in Sec. 6. Eventually, a brief summary will be given in Sec. 7.

2. Principle

The mechanism of a classical radio telescope is very similar to that of an typical optical reflector telescope. It is easy to achieve homophase focusing by using a rotating paraboloid as a mirror, therefore, most of the radio telescope antennas are paraboloidal. Radio telescope surface and an ideal paraboloid of the mean square error rate is not greater than $\lambda / 16 \sim \lambda / 10$, the telescope can generally work effectively in the wavelength greater than λ radio band. For meter-wave or long-division meter-wave observations, a metal mesh can be used as the mirror, while for centimeter-wave and millimeter-

wave observations, a smooth and precise metal plate (or coating) is required as the mirror [9]. A typical sketch of the principles is shown in Fig. 1 [10].

Radio telescope consists of four main parts: antenna system, receiver, data acquisition system and computer, among which the antenna system is the most important. According to the source of received information, the radio telescope determines the position of the observation object, and changes the direction of the main reflector through the support and the pitching mechanism to track the signal. The primary and secondary reflector surfaces are used to receive celestial radiation and reflect the collected celestial radiation to the feed source. The feed source converts the collected radiation wave into current after polarization filtering and transmits it to the receiver. The receiver will amplify and process the current and transfer it to the data acquisition system, and finally transmit it to the computer for people [3].

The performance of radio telescope is described by two main indexes, sensitivity and resolution. Sensitivity refers to the minimum energy that can be measured by a radio telescope in its work. The smaller the value, the higher the sensitivity and the better the observation ability of the radio telescope. Resolution is the ability of a radio telescope to distinguish between two radio sources that are close to each other. The two working indexes of radio telescope can be improved by improving the receiving equipment and changing the receiving area of the reflection surface. The most effective method is to increase the aperture of radio telescope. At present, there are two ways to increase the aperture of radio telescope. One is to build a single radio telescope with larger reflector aperture, and the other is to use the principle of interferometer to build an array radio telescope to achieve the purpose of increasing the receiving area. At present, both methods have been used in the world. While researching larger monomer radio telescopes, some array radio telescope networks, such as the Square Kilometer Array Radio Telescope (SKA) and the East Asian Very Long Baseline Interferometry (VLBI) observation project, have also been established internationally.

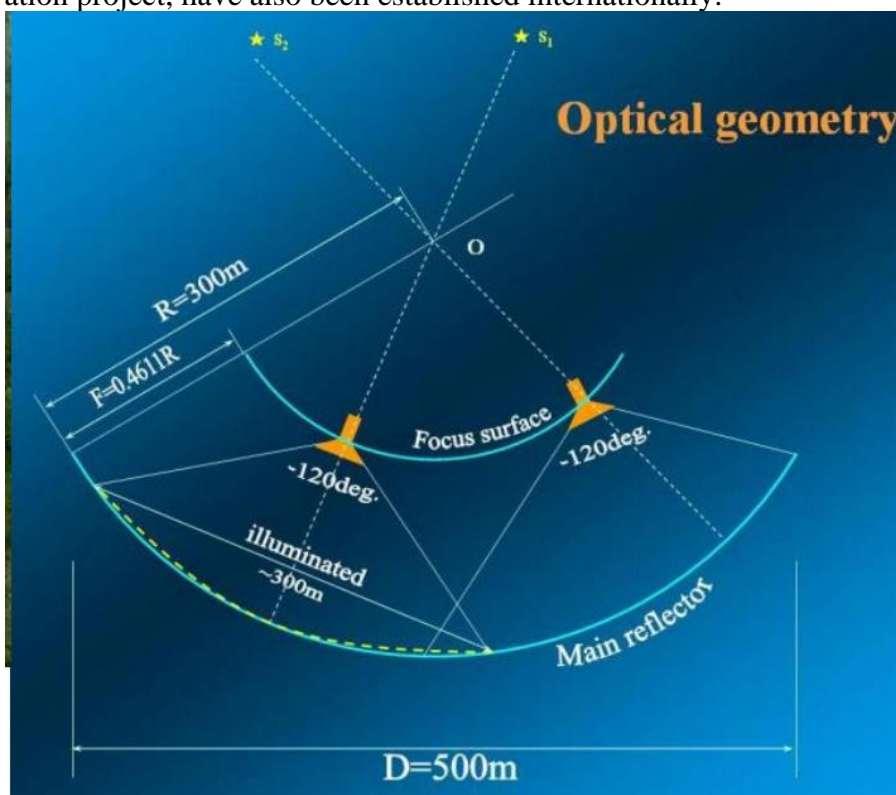


Fig. 1 A schematically diagram of radio telescope [9].

3. Arecibo Radio Telescope

The Official name of the Arecibo Radio Telescope in the United States is the Arecibo Observatory, which was officially put into operation on November 1, 1963, with an aperture of 305 meters, and

was later expanded to 350 meters. Before the completion of the China FAST, it maintained the title of the world's largest single-aperture radio telescope. Because its caliber is too large to stand on its own, it was built in a natural volcanic crater on the island of Puerto Rico. Since it cannot be rotated, it is necessary to use a spherical main mirror to use different parts of the "pot" to scan celestial objects in different directions. Since the spherical plane cannot concentrate electromagnetic waves at a single point like a parabolic plane, it can only converge on a single line and then use a complex and cumbersome feeder capsule to collect signals. So, when a main steel cable suspends a 900-ton feeder chamber (the FAST feeder compartment weighs only 30 tons) in November 2020

When a rupture occurred on the 6th, it caused the most fatal blow. Until December 1, the support platform is complete. The bottom collapsed and the feed capsule fell to the main reflective surface, leaving Arecibo scrapped. For more than half a century, the Arecibo Observatory has undergone several upgrades and has been a research center for astronomy and atmospheric sciences. He studied the Earth's ionosphere, received radio wave signals from distant universes, and used radar techniques. Techniques explore objects within the orbit of Saturn in the solar system [11].

The Arecibo Radio Telescope is equipped with a powerful radio transmitter. The huge antenna has a very high directionality, so that the radio waves gather into a very small beam of radiation to be emitted, and the directional transmission can greatly increase the transmission power. Radio waves are reflected back when they hit solid objects, but the energy of the echoes is small and requires a very sensitive radio telescope to receive them. It is precisely because of the characteristics of this telescope that it has become the most powerful radar in the world. On the 10th anniversary of the telescope's construction, under the auspices of the famous astronomers Carlsagan and Drake, a string of 1679 binary numbers was sent to the center of the globular cluster M13, 250,000 light-years away from Earth, and if the aliens could correctly decode this string of information, they would obtain a series of numbers and graphics that could help aliens have a basic understanding of The Earth. It contains ten numbers from 1 to 10 in binary representations, the chemical formula of nucleotides, the double helix shape of DNA, the human shape, the composition of the solar system, and so on. This information is called are Arecibo information [12].

Arecibo's location in a limestone crater in Puerto Rico's karst landscape provided the perfect place to build a huge monolithic radio telescope, and because Puerto Rico was relatively backward in economic development, electromagnetic environmental disturbances were superior to those of the Continental United States in the 1950s. Looking for natural karst terrain as the site of large telescopes, it is because the huge telescope is a sophisticated radio technology equipment, which requires a stable surrounding geological environment, the surrounding radio clutter interference is blocked, and the underground water permeability performance is good to avoid flooding, and the karst just meets these harsh conditions. A sketch of it is illustrated in Fig. 2 [13].



Fig. 2 A sketch of Arecibo Radio Telescope [13].

4. FAST

FAST has been under construction since 2011, and was completed in 2016. A sketch of it is presented in Fig. 3. A 500-meter radio telescope, if installed on a flat ground, needs to establish a very large support mechanism, which will be a labor-intensive, time-consuming, and cost-consuming project. The karst terrain in Guizhou region of China which it is located in is both a natural depression and a natural funnel, with a good natural drainage system. In addition, the sparse population and low radio pollution facilitate the establishment of radio isolation zones. FAST 500meter diameter spherical mirror cannot be processed into a whole mirror surface. The main reflective surface of FAST is designed to be composed of 4450 small mirror units (referred to as unit blocks), each unit block is a small part of the shape of a 500-meter spherical mirror, and after splicing, the main reflective surface (cauldron) of a large spherical telescope with a diameter of 500 meters is formed. The element block of the reflective surface is not a simple small panel, but a component composed of a frame, purlin and a small panel. Due to the different positions of the reflective panel element blocks on the overall spherical mesh, their geometric inclination angles, support point positions, load sizes and directions are different. Therefore, a computer-controlled actuator is installed at the junction of each element block member, which can apply different forces to adjust the geometric structure of each small unit block on the overall layout to achieve the same accuracy requirements of the overall surface type [14].

FAST uses the unique Guizhou natural karst depression site, applies active reflective surface technology to correct the difference on the ground, and proposes to use a light feeder support system with opto-mechatronics to achieve accurate positioning of the feed. The feeder support system is mainly used to achieve precise positioning of the feeder through a 6-cable drive mechanism and a feeder chamber, where the two main mechanisms in the feeder chamber are the AB shaft mechanism and the Stewart platform. According to the trajectory planning scheme of the feeder support system, the motion control of the feeder support system can be divided into coarse positioning and fine adjustment positioning. The coarse-tuned positioning is carried out by a 6-cable drive mechanism and an AB shaft mechanism, i.e., three anchor head supports of the feeder chamber are connected by 6 steel cables of several hundred meters, and the cable drives the feeder chamber with a diameter of 13 m on the focal surface with a span of about 206 m, and realizes the astronomical trajectory planning of the feed source together with the AB shaft mechanism. In astronomical observation, the positioning accuracy of the feeder directly affects the observation efficiency of the feeder, because the 6-wire

parallel mechanism is a low stiffness mechanism, the cabin cable system is susceptible to wind disturbance, according to the research analysis of the coarse positioning maximum position error of up to 48 mm [15].

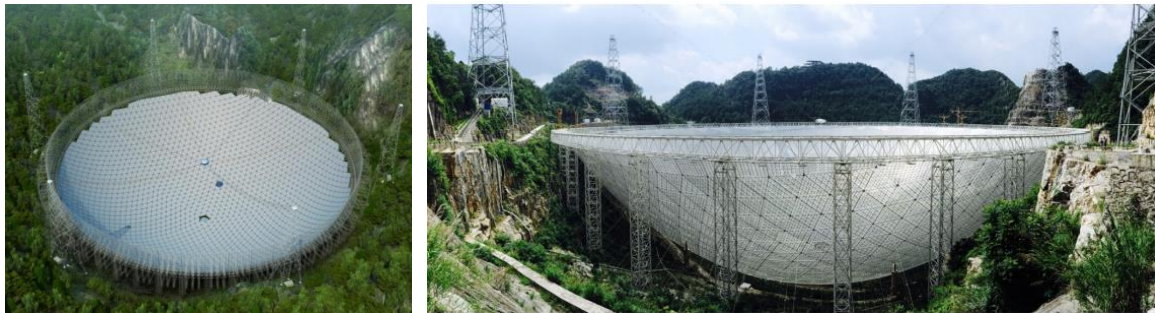


Fig. 3 A sketch of the FAST [9].

5. Comparison

As a matter of fact, the two state-of-art detectors (i.e., Arecibo and FAST) varies a lot in detection ability and features for observation. A comparison table is given in Table. 1. For comparison, FAST is located in China's Yunnan-Guizhou Plateau, where the karst topography is extremely intact and the geological conditions are superior to the environment of the Arecibo site, which is the world's best candidate for large-scale single-aperture telescope sites. In addition, Guizhou's economy is in a backward area of domestic development, the construction cost of large scientific projects is low, and the radio environment in Guizhou's mountainous areas is very quiet, less interference, and easy to protect. Therefore, Guizhou's hardware conditions can be described as unique, while the United States lacks a complete karst landform, which is beyond reach. Arecibo reflective surface is a fixed spherical surface, which makes its reflected electromagnetic waves cannot be automatically focused, American astronomers designed an additional system, in the high altitude away from the reflective surface to add a secondary reflection system, and then the received signal converged to the focus, which led to Arecibo hanging receiving feed system is unusually large and bulky, weighing up to 1000 t.

The feeder system of this weight consists of 18 steel cables suspended from the surrounding 3 support towers, which makes the steel cable fatigue problem stand out. When the telescope is hit by a typhoon, if the feed source is not recovered in time, then soft injury strain will occur, and over time, the risk of a fracture accident increases. The collapse of Arecibo's support tower is related to the typhoon in August 2020, which has caused a steel cable to break, and the lack of follow-up maintenance has led to a large-scale rupture and collapse on December 1, 2020, resulting in irreparable consequences. Fast at the beginning of the design, has taken into account the defects of Arecibo, so there are 6 support towers, increasing the safety factor. FAST's most prominent innovation is that its telescope structure is very dexterous, the reflective surface is designed as a deformable 4450 movable panels, through the panel position adjustment to achieve focus, directly turning the spherical surface into an instantaneous parabolic surface, so that the weight of the receiving feed is greatly reduced, only 30 t. At that time, early builders of FAST such as Nan Rendong realized that if the structure of FAST mimicked Arecibo, the weight of its feeder receiving system would be as high as 3000 t, which was a behemoth that could not accurately move operations, so other ingenious design schemes had to be found to reduce the pressure on the support system [16].

Table. 1 Comparison table of the two telescopes [16]

Compare content	Arecibo	FAST
Location	Puerto Rico, United States	Guizhou, China
Site conditions	Geological conditions Beach Rock Earthquake risk exist natural disaster hurricane	Triassic limestone rare rare
	Aperture/Effective Radius/m	500/300
	Feeder support	Six-wire drive intelligent platform
Structural performance	Reflective surface features Fixed emission surface	Active reflective surface
	Operating frequency/GHz	0.07~3
	Zenith angle / (°)	20 40
	Continuous tracking duration/h	2 4
	Support structure mass/t	900 30

The precision control mechanism of the feeder module is the Stewart platform, so the accuracy analysis study of the feeder cabin can be simplified to the accuracy analysis study of the Stewart platform. The Stewart platform is a typical paralleling mechanism, which is a new type of mechanical device that was born and gradually developed in the 1940s, and the earliest proposed parallel mechanism is the Gough-Stewart institution [17, 18]. Parallel mechanism has the advantages of high stiffness and high precision, with the development of computer and control technology, parallel mechanism has been successfully applied in many fields such as robot operators, machine tools, engineering equipment, scientific equipment, etc., and its accuracy can be much higher than RMS 10mm [19-21].

However, the Stewart platform in the feedthrough cabin has its own peculiarities: the feeder chamber is a trajectory movement under the traction of a large-span zoline mechanism, the natural frequency of the cable mechanism is low, the mechanism is coupled with each other and is susceptible to wind disturbance. Based on the safety and design parameters of the cable parallel mechanism, the quality of the feeder chamber is limited to less than 30 t, which makes it difficult to obtain a high stiffness in the optimization design of the feeder chamber, so the structural deformation of the Stewart platform is higher than that of the Stewart platform used in the traditional industrial field, and it is necessary to analyse the impact of structural deformation on positioning accuracy in combination with the control scheme. At the same time, due to cost and construction period constraints, it is impossible to build a prototype of a complete feeder support system for direct accuracy verification tests, and some similar models of the FAST feeder support system previously built cannot be used to verify the accuracy of the Stewart platform [15].

6. Limitations & Future prospects

For single-aperture submillimeter wave antennas, the demand for antenna aperture is increasing in order to improve their sensitivity and spatial resolution. However, existing submillimeter-wave single-antenna telescopes are small (10-15 m) in aperture, so resolution and sensitivity are low. At the same time, most submillimeter-wave telescope antennas have a small field of view, and the sky survey ability of large sky areas is weak. This has led to submillimeter survey capabilities and results lagging far behind other major astronomical bands, which is a long-term shortcoming and blank in the field of astronomy. In order to fill this gap, many large submillimeter wave antenna construction plans came into being. These submillimeter-wave large single-antenna telescopes offer the

advantages of high sensitivity and fast sky survey with large field of view. At present, high-precision submillimeter-wave telescopes (JCMT, CSO, etc.) mostly use active surface technology to correct gravity deformation and thermal deformation [22], but are more limited to correcting the deformation of the main panel under the influence of gravity. Limited by the bottleneck of the current wave surface real-time measurement technology, the existing active surface technology plays a very limited role in correcting the wavefront difference caused by the wind load and temperature of the high-precision antenna. In addition, existing submillimeter wave antennas have smaller apertures, and they all use antenna protectors to reduce the partial impact of wind on the structure. But adding a radome is too costly for large submillimeter-wave telescopes, so other methods and techniques are needed. The structural oscillation caused by wind disturbance can only be reduced by strengthening the stiffness of the antenna structure; Through the antenna servo control system to compensate for the deformation of the rotation around the axis, the control algorithm and motor requirements are very high, the proposed PID control, LQG control and H infinite control and other control algorithms [23-25]. In the high-frequency band telescope engineering application is less, most of them are simulation analysis, especially for large submillimeter wave telescopes, not only the control algorithm to effectively improve the antenna wind disturbance ability, but also need to match the control algorithm antenna mechanical properties and control performance [26], but there is no technology that can be successfully applied. In order to meet the index requirements of large-aperture high-precision submillimeter-wave telescopes and effectively reduce the deformation caused by factors such as temperature load and wind load, new breakthroughs must be made in methods and technologies.

7. Conclusion

In conclusion, this paper demonstrates the basic principles of telescopes and gives a detail description and comparison of the two state-of-art telescopes (i.e., Arecibo and FAST). In detail, FAST uses abbreviation for Five-hundred-meter Aperture Spherical radio Telescope. According to the analysis, for the time being, all radio telescopes, regardless of the type of telescope, have significant problems in various aspects. In the future, With the development of the times and breakthroughs in key technologies, the technology of radio telescopes can definitely have a good development.. Overall, these results offer a guideline for future designs of telescopes.

References

- [1] Merrifield M R, Saari D G. Telescope time without tears: a distributed approach to peer review. *Astronomy & Geophysics*, 2009, 50(4): 4.16-4.20.
- [2] Shetrone M, Cornell M E, Fowler J R, et al. Ten Year Review of Queue Scheduling of the Hobby-Eberly Telescope. *Publications of the Astronomical Society of the Pacific*, 2007, 119(855): 556.
- [3] Kosowsky A. The atacama cosmology telescope. *New Astronomy Reviews*, 2003, 47(11-12): 939-943.
- [4] Sutherland W, Emerson J, Dalton G, et al. The visible and infrared survey telescope for astronomy (VISTA): design, technical overview, and performance. *Astronomy & Astrophysics*, 2015, 575: A25.
- [5] Gehrz R D, Roellig T L, Werner M W, et al. The NASA Spitzer space telescope. *Review of scientific instruments*, 2007, 78(1): 011302.
- [6] Johns M, McCarthy P, Raybould K, et al. Giant magellan telescope: overview. *Ground-based and Airborne Telescopes IV*, 2012, 8444: 526-541.
- [7] Swarup G, Ananthakrishnan S, Kapahi V K, et al. The giant metre-wave radio telescope. *Current science*, 1991, 60(2): 95-105.
- [8] Ellingson S W, Taylor G B, Craig J, et al. The LWA1 radio telescope. *IEEE Transactions on Antennas and Propagation*, 2013, 61(5): 2540-2549.
- [9] Marr J M, Snell R L, Kurtz S E. *Fundamentals of radio astronomy: observational methods*. CRC Press, 2015.

- [10] Nan R, Li D, Jin C, et al. The five-hundred-meter aperture spherical radio telescope (FAST) project. *International Journal of Modern Physics D*, 2011, 20(06): 989-1024.
- [11] Amley Arecibo's Life Story (Part 1). *Encyclopedia Knowledge*, 2021(02):26-27.
- [12] Lu J. What Arecibo telescope is used for. *Fangyuan*, 2020 (18) : 8.
- [13] Clery D. Arecibo radio telescope to be decommissioned. 2020.
- [14] Guo Hongfeng. China's "Eye of Heaven": 500 meter Aperture Spherical Radio Telescope. *Military Abstracts*, 2021(16):52-55.
- [15] Yao Rui, LI Qing-wei, SUN Jing-hai, SUN Cai-hong, ZHU Wen-bai. Accuracy analysis of feed chamber of FAST telescope. *Journal of mechanical engineering*, 2017, 53(17):36-42.
- [16] Zhang Chengmin, Cui Xianghan, Yang Yyan, Wang Dehua. From arecibo to China's sky telescope: relay of industrial revolution *Science and technology review*, 2021, 39(11): 9-15. (in Chinese).
- [17] HUANG Zhen, KONG Lingfu, FANG Yuefa, et al. *Theory and control of parallel robot mechanism*. China Machine Press, Beijing, 1997.
- [18] Fichter E F. A Stewart platform-based manipulator: general theory and practical construction. *The international journal of robotics research*, 1986, 5(2): 157-182.
- [19] SHAO Zhufeng, TANG Xiaoqiang, CHEN Xu, et al. Research on the inertia matching of the Stewart parallelmanipulator. *Robotics and Computer Integrated Manufacturing*, 2012, 28(6): 649-659.
- [20] YAO Rui, TANG Xiaoqiang, LI Tiemin, et al. Erroranalysis and distribution of 6-SPS and 6-PSS reconfigurable parallel manipulators. *Tsinghua Science and Technology*, 2010, 15: 547-554.
- [21] XIE Ping, DU Yihao, TIAN Peitao, et al. A parallel robot error comprehensive compensation method. *Journal of Mechanical Engineering*, 2012, 48(9): 43-49.
- [22] SMITH I A. JCMT active surface control system: implementation. *Telescope Control Systems III*, Kona: SPIE, 1998: 190-196
- [23] GAWRONSKI W. Control and Pointing Challenges of Large Antennas and Telescopes. *IEEE Transactions on Control Systems Technology*, 2007, 15(2): 276-289.
- [24] GAWRONSKI W. *Modelling and Control of Antennas and Telescopes*. New York: Springer, 2008.
- [25] Du Biao, Wu Yang, Zhang Yifan, et al. Overview of large aperture reflector antenna technology. *Radio communication technology*, 2016, 42 (1): 1-8.
- [26] Zhang Jie. *Study on Key Technologies of wind disturbance resistance control and Compensation for large Reflector antenna*. Xidian University, 2016.
- [27] Zhang Mingzhu, WANG Hairen, Zuo Yingxi, Gao Jingjing. Review of radio telescope structure technology development. *Journal of Huazhong University of Science and Technology (Natural Science Edition)*: 2022, 1-12.