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FAST: The Five-Hundred-Meter Aperture Spherical Radio Telescope

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In the 90 years since its inception, radio astronomy has become the setting of almost all major astronomical discoveries and a hothouse for Nobel Prizes in Physics. As a result, countries all over the world have actively explored new engineering concepts to build large-aperture radio telescopes. Limited by their self-weight and wind load, 100 m radio telescopes are regarded as the maximum limit of traditional radio telescopes. This perspective allowed the Arecibo 305 m telescope—built by Cornell University in the United States in 1963—to dominate the field for more than half a century. During this period, scholars have been exploring how to further expand their horizons in order to make a breakthrough in the problem of the universe.

Against this background, the idea of a five-hundred-meter aperture spherical radio telescope (FAST) was put forward in 1994 and was then designated as a major scientific and technological infrastructure construction project in China during the 11th Five-Year Plan in 2007. The construction of FAST started in 2011, and the telescope passed the national acceptance on 11 January 2020 [1–3]. As a radio telescope with independent intellectual property rights in China, and as the largest and most sensitive single-dish radio telescope in the world, the development of FAST has led to many important technological breakthroughs with influential scientific research outputs across the globe [4], helping to realize the originality and development of cutting-edge scientific research in fields such as radio astronomy in China [5–10].

1. The working principle and important achievements of FAST

Adopting a brand-new design concept, FAST has been built as the largest single-dish radio telescope in the world. FAST works in an extremely unique way (Fig. 1). Its huge reflecting surface is supported by a cable net, while 2225 actuators below the reflecting surface can control the cable net to form a 300 m aperture illuminated paraboloid. Six steel cables are used to form a cable-parallel robot to tow a 30 t feed cabin equipped with feed receivers. An AB rotator and Stewart platform in the feed cabin further expand the observation zenith angle of the feeds, improve the positioning and pointing accuracy, and ultimately position the feed receivers at the focus position of the paraboloid with high accuracy, so as to collect the electromagnetic wave signals gathered by the paraboloid.

Different paraboloid positions represent different observation directions (Fig. 2 for the principle of geometric optics). In a word, FAST puts forward a brand-new design concept and adopts an innovative active reflector system and feed support system that integrates optical, mechanical, and electrical features. Coupled with the unique advantages of its site, FAST represents a new mode of building giant radio telescopes, breaks through the 100 m diameter engineering limit of traditional telescopes, and covers a sky area of ±40° with relatively flexible pointing.

Although FAST is a rare super-large-structure project in terms of engineering volume, it is also a type of high-precision astronomical observation equipment in terms of accuracy. Thus, its engineering construction presented the difficult dilemma of maintaining a balance between accuracy requirements and engineering volume. Moreover, the project is located in an extremely complex mountainous environment in Guizhou (China). China is a world leader in engineering construction technology in the industrial sector. Nevertheless, a considerable degree of innovation has been required for the FAST project. The new technologies developed for this project include: high-altitude combination and sliding installation technology for super-large-diameter ring beams under complex terrain conditions; a high-altitude accumulation and sliding assembling method for complex cable nets; and a reflective surface unit that is self-adaptive to cable net displacement, along with its installation technology. In particular, the construction technology for ring beams has been approved as a national engineering method.

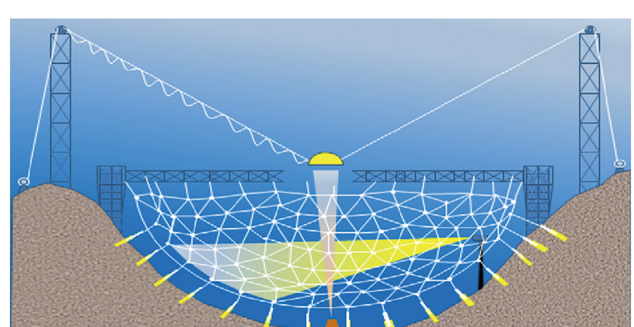

Fig. 1. Schematic diagram of the working principle of FAST.

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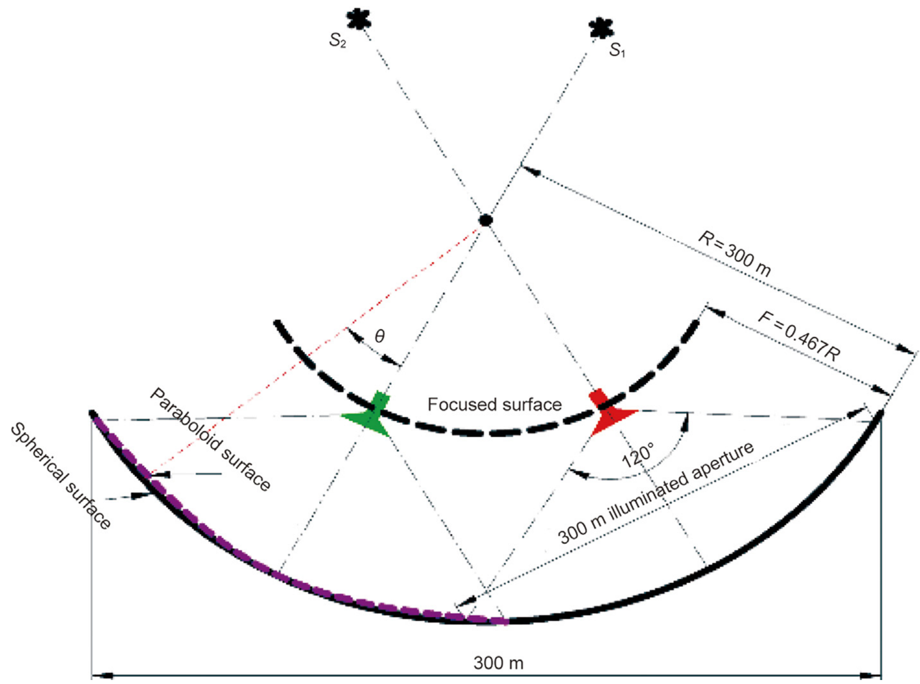

Fig. 2. The geometric optical path principle of FAST. S_1, S_2: observation targets; *R*: curvature radius of the reflection surface; θ: observing zenith angle; *F*: focal ratio.

FAST's special working mode has extremely specific requirements in terms of materials and important components. For example, the FAST team has developed a steel cable with ultra-high fatigue resistance in order to realize deformation of the cable net of the active reflector, with a fatigue strength reaching a stress amplitude of 500 MPa under a cyclic loading test of two million cycles, which is 2.5 times higher than the domestic and international standards and specifications. The team has mastered the key technology for large-core, ultra-stable, and bendable optical cables in order to realize coaxial signal transmission of the feed source, achieving a bending fatigue life of 100 000 times, which is 100 times greater than that required by the national military standard, with the real-time fluctuation of signals being less than 0.05 dB.

In terms of measurement and control technology, the FAST system is extremely complex, operates in a harsh outdoor climatic environment, and must realize all-weather dynamic measurement and control on a kilometer scale; thus, it poses a difficult technical challenge in terms of industrial measurement and control. To solve the engineering technology problems in FAST's measurement and control, the FAST team first developed automatic observation technology with a double-target mutual-aiming mode, which eliminates the influence of atmospheric refraction and other factors while ensuring sub-millimeter positioning accuracy of the control network on a kilometer scale. Next, the team developed a multi-system data fusion and measurement system based on an inertial measurement unit (IMU), a global navigation satellite system (GNSS), and a total station positioning system (TPS). The system makes use of the complementary advantages of different technical means to achieve high-precision, all-weather, and highly dynamic measurements of the position and attitude of the feed cabin. Finally, the FAST team proposed and realized a reflective surface control method based on mechanical simulation technology and established a measurement and control system for large telescopes that is suitable for FAST's special working mode.

The key technologies mentioned above supported the completion of FAST's main construction while meeting all technical requirements. More specifically, FAST's sensitivity has reached a level that is 2.5–3.0 times greater than that of the American Arecibo Telescope. Since being put into operation in February 2020, FAST has discovered more than 660 pulsars—more than four times the pulsars discovered by all other telescopes in the world during the same period. A series of high-level papers on FAST's achievements regarding fast radio bursts have been published in *Nature* and *Science*, deeply influencing scholars' knowledge of these astronomical phenomena. This new information on fast radio bursts was rated as one of the top ten scientific breakthroughs and discoveries in 2020 by *Nature* and *Science*, respectively; it was also rated as one of the top ten scientific and technological advances in China by the academicians of the Chinese Academy of Sciences and the Chinese Academy of Engineering in 2021. In addition, FAST detected the magnetic field distribution in the Taurus molecular cloud with high confidence for the first time, providing new and important observational evidence for solving the magnetic flux problem—one of the three classic problems of star formation. The report on this achievement was published as the cover paper in *Nature*.

To summarize, FAST has produced a series of internationally influential scientific achievements in the fields of pulsar search, fast radio bursts, and galaxy formation and evolution. The telescope has been opened to astronomers all over the world, becoming an important observation apparatus in the field of international radio astronomy. Its related technologies have also significantly facilitated technological development in engineering construction, materials, measurement, and other related fields. Some of these key technologies have achieved market-oriented popularization and application, resulting in remarkable social and economic benefits. Regardless, the FAST team will continue to work on performance improvement and function expansion in the future.

2. Important technological developments related to FAST

2.1. Performance improvement

2.1.1. Developing proprietary controllable phased array receiver technology to improve the telescope's survey efficiency

It is well known that the larger the aperture of a telescope is, the smaller its field of view will be. FAST's effective aperture is 300 m, and its field of view at an observation frequency of 1.4 GHz is only three arc minutes. To solve the problem of telescope sky survey efficiency, FAST currently uses a 19-beam receiver to expand the field of view to 19 times that of the original single beam. However, the working frequency band of the multi-beam receiver is generally narrow. At present, the working frequency range of the 19-beam receiver is 1.05–1.45 GHz, which greatly restricts the scientific goal for FAST. Therefore, it is of great practical significance to develop a receiver technology for FAST with a large field of view and wide frequency band.

Based on the actual demand and technical development trend of FAST, the FAST team is developing a phased array receiver system with a wide bandwidth and large field of view [11,12], whose frequency coverage reaches 1.1–3.3 GHz and whose field of view coverage is ≥ 0.25 square degrees. This system will raise the above two indexes of FAST to five times and ten times the current level, respectively, greatly improving FAST's sky survey efficiency. Taking the Galactic Plane Sky Survey Project of FAST as an example, the project is allocated 600 h every year and will require ten years to achieve complete coverage of the galactic plane under current conditions. The successful development of the phased array receiver, however, will shorten this period to just one year. Moreover, the frequency coverage is expected to increase by five times, which can theoretically at least double the pulsar timing accuracy. This advance will play an important role in promoting the establishment of a pulsar time reference and the detection of low-frequency gravitational waves.

Molecular spectral lines, such as neutral hydrogen, OH maser, and formaldehyde, are present in the 1.1–3.3 GHz frequency band and are important probes for studying scientific issues related to galaxies and cosmology, and the formation of stars and planets at different cosmic scales. Some spectral lines of long-chain molecules such as HC7N and HC9N also fall within this frequency band. Observing these spectral lines will help scientists understand the distribution, abundance, and evolution of organic macromolecules in interstellar media and will provide clues for detecting organic macromolecules related to the origins of life.

2.1.2. Realizing all-weather high-precision measurement via telescope with a feed source position and attitude measurement technology based on microwave ranging (MR)

It is necessary to develop new, high-precision measurement technology in order to expand the scientific observation ability of telescopes to 3.3 GHz. A TPS is a specialized optical measurement technology for static measurement. Its accuracy can only reach about 10 mm in FAST's dynamic application scenarios, and it is easily affected by climate [13]. MR measurement featuring dynamic and all-weather functioning holds potential for development to a high-precision level. If the TPS is replaced by MR, and if a new data fusion and measurement system for the GNSS/IMU/MR is realized on this basis, it will be possible to achieve all-weather and high-precision position and pose measurement of the feed source system. Regarding MR, however, there is as yet no mature technology to achieve millimeter-level dynamic accuracy [14]. Therefore, the research and development of millimeter-level MR technology holds great practical significance for telescopes in their expansion to a higher observation frequency band.

FAST uses a new multi-system data fusion and measurement system based on micro-ranging technology, and the plan is to use a dual-frequency method for ranging in order to find a balance between measurement accuracy and the calculating difficulty of integer ambiguity. The atmospheric refractive index is less than 3 ppm, and the MR accuracy is better than 3 mm. After data fusion, the positioning accuracy of the feed fine-tuning platform will be better than 5 mm, and the angle accuracy will be better than 0.1°. This will provide high-precision phase center measurement results for the telescope at all times, improve the stable output ability of the telescope with high pointing accuracy, provide strong technical support for the expansion of FAST to a higher observation frequency band, and offer assistance to scientists in high-precision mapping of the midline hydrogen spectrum.

2.1.3. Upgrading FAST's feed cabin and expanding its observation range

At present, FAST's maximum observation zenith angle is 40°. If FAST's maximum observation zenith angle can be increased to above 50°, which is close to or even covers the galactic center, it will be possible to discover more maser sources near the galactic center, which will help scientists understand the star-formation process in this special area. Furthermore, it will be possible to discover pulsars revolving around supermassive black holes, which will help us understand the electron density near the galactic center, measure the basic parameters of supermassive black holes, and verify the general theory of relativity under more extreme conditions. It is also worth noting that, based on the development and use of phased array receivers and the new development direction and requirements of FAST radar astronomy, the feed cabin after weight reduction can be used for new receivers and other important equipment, allowing FAST to achieve higher observation performance.

It has been proposed that FAST's rigid fine-tuning platform—that is, the AB rotator plus Stewart platform—in the feed cabin be replaced by a cable-parallel robot. The main structure will be a six-cable-parallel robot to realize low-speed and large-angle movement, which will improve feed cabin's the dynamic characteristics with a down cable or branched-chain mechanism. Through performance matching, FAST will achieve an observation zenith angle of more than 50° [15,16] and has an installation margin of more than 4 t of new equipment. The new robot will be able to more reliably ensure the stable and high-precision positioning and tracking of the feed receivers. With the use of new feed receivers and high-precision measurement technologies, FAST's overall performance will be greatly improved.

2.2. Developing new functions

2.2.1. Opening up new directions in radar astronomy

Radar astronomy is a new branch of astronomy that uses the principle of radar detection to study natural and human-made objects in near-earth space and the celestial bodies in the Solar System. It actively transmits radio waves and receives the reflected echoes of the targets. Radar astronomy can also detect targets that are not irradiated by visible light and are in the "shadow," a term that refers to areas that cannot be reached by means of optical detection. In addition, electromagnetic waves have penetrating ability in some low-frequency bands and can be used to detect geological morphological information about the shallow region below the surface of celestial bodies. Moreover, by measuring the time delay, Doppler, and polarization information of echo signals, radar astronomy can be used to accurately determine the orbits and produce high-resolution images of distant targets with a performance several orders of magnitude higher than that of optical detection, making this research content unique to the field of radar astronomy. With its high sensitivity, FAST is naturally suitable for radar astronomy exploration and can be used to carry out bistatic or multi-static observation with the help of existing high-power transmitting radar. FAST's observation will play an important role in research on the top ionosphere, lunar exploration, space debris detection, and near-earth object detection.

FAST will be used to carry out joint detection with incoherent scatter radar. Given FAST's receiving ability, the top ionosphere can be detected at more than 1000 km altitude, making FAST one of the few devices in the world that can detect the top ionosphere. In regard to lunar exploration, the focus of radar astronomy has shifted to the moon's south pole, which is the most promising place for building a lunar base in the future; radar astronomy can be used to detect the distribution and content of water and ice in the permanent shadow area of the south pole of the moon. FAST's joint detection can improve space debris detection to an accuracy of less than 1 cm. It is expected that FAST will be able to detect fainter near-earth objects, especially those that are difficult to detect outside of the sunshine area; this will be a useful supplement to optical detection methods and can be used to accurately determine the shape of near-earth asteroids and to obtain high-resolution imaging and the three-dimensional terrain characteristics of near-earth asteroids.

During FAST's overall upgrading in the future, if it is possible to expand the high-power transmission function in the L or S band with reference to the Arecibo Telescope, FAST's detection capability will be improved by a further order of magnitude according to the radar equation.

2.2.2. Building a pulsar timing array and setting new time and frequency standards

At present, the most commonly used time and frequency standard is the International Atomic Time, whose time-measuring accuracy is as high as 3×10^{-16}. However, atomic time is not perfect, because its stability decreases due to the aging of the atomic clock, and there is no other time standard that can be used for comparison with it at present. Therefore, it is urgent to establish an independent time standard whose accuracy exceeds that of atomic time. The rotation of pulsars in the Milky Way is extremely stable, and the time based on pulsar signals naturally possesses ultra-high time–frequency stability [17]. Observation data for different pulsars can be compared, so the accuracy of the pulsar time will not depend on atomic time, allowing the pulsar time standard to be independent of atomic time. FAST has extremely high sensitivity, can obtain time-measuring data with an ultra-high signal-to-noise-ratio in pulsar observation, and is very suitable for carrying out pulsar time–frequency work. It can greatly improve the accuracy of time measuring for pulsars and speed up the establishment of a pulsar time standard [18].

FAST combines the existing algorithms of various related pulsar data-processing programs, rewrites the time-measuring module, unifies the data-processing flow, and reconciles the conflicts among different programs. The new pulsar data-processing program adopts a new data structure and file structure; the former helps in adjusting parameters and analyzing data in the process of timing and time–frequency analysis, while the latter helps in carrying out data storage, management, and analysis.

While FAST is used for pulsar timing to establish a pulsar time standard, the FAST pulsar timing database can be built. The applications of this database cover a number of aspects. For space exploration, the pulsar timing database can lay a good foundation for pulsar navigation technology. In astronomical research, the pulsar timing database can be used to improve the calculation of Solar System ephemeris, search for unknown celestial bodies in the Solar System, and search for extragalactic gravitational waves at an extremely low frequency [19].

3. Future prospects of FAST

Focusing on the actual needs in radio astronomy technology and methods, the FAST team has tailored a research plan. In the next 3–5 years, a new generation of the phased array receiving system will be developed, which will grant the telescope a large field of view and broadband, and will improve the efficiency of the telescope's sky survey by a few orders of magnitude. New feed position and pose measurement technology based on MR will provide the telescope with a stable output ability and high pointing accuracy at all times, while giving FAST strong technical support to expand to a higher observation frequency band. The completion of the newly upgraded feed source cabin will expand FAST's observed sky area and greatly improve coverage of the telescope's scientific targets. FAST's technical development in radar astronomy is likely to play an irreplaceable role in earth-approaching object warning and planetary science. Based on FAST's super-sensitivity, the time measurement accuracy of pulsars will be improved to 40–50 times that of other instruments. The high measurement accuracy of pulsars will make it possible to establish a time reference system based on pulsar time and to carry out multi-field research based on the pulsar timing array. The upgrading of these technologies will speed up innovative breakthroughs in scientific fields such as radio astronomy.

FAST possesses unique competitiveness for the observation and research of a wide range of astronomical phenomena, ranging from the initial turbidity of the universe to dark matter, dark energy and large-scale structures, the evolution of galaxies and the Milky Way, stellar objects, and even the planets of the Solar System and adjacent space events. It will answer scientific questions that not only are astronomical but also target humankind and nature, and is expected to enable very promising scientific discoveries. Array research using FAST is also underway. Hopefully, astronomical interferometry technology will be able to network a number of high-performance radio telescopes to form a super-giant telescope whose resulting high sensitivity and high-angle resolution will lead the world in radio astronomy and help astronomers produce further high-quality research results.

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