The Five-hundred-meter Aperture Spherical radio Telescope (FAST) project

Rendong Nan1,2 and Di Li1,3

1. National Astronomical Observatories, Chinese Academy of Sciences, A20 Datun Road, Chaoyang District, Beijing 100012, China
2. Key Laboratory for Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, China
3. Space Science Institute, Boulder, CO 80301, USA

E-mails nrd@bao.ac.cn dili@nao.cas.cn

Abstract: Five-hundred-meter Aperture Spherical radio Telescope (FAST) is a Chinese “mega-science” project to build the largest single dish radio telescope in the world. Its engineering concept and design pave a new road to realize a huge single dish in an effective way. Being the most sensitive single dish radio telescope, FAST will enable astronomers to jump-start many science goals, such as surveying the neutral hydrogen in the Milky Way and other galaxies, detecting faint pulsars, hearing the possible signals from other civilizations, etc. The feasibility studies for FAST have been carried out for 14 years, supported by Chinese and international astronomy communities. The National Development and Reform Commission approved the funding proposal of FAST in 2007 with a capital budget close to 700 million RMB. The project time is 5.5 years from the commencement of work in March of 2011 and the first light is expected in 2016.

1. Engineering concept of FAST

FAST is an Arecibo-type antenna with three outstanding aspects: the karst depression used as the site, which is large enough to host the 500-meter telescope and deep enough to allow a zenith angle of 40 degrees; the active main reflector correcting for spherical aberration on the ground to achieve a full polarization; and a wide band without involving complex feed systems. If we adopt Arecibo design, we would need 10000 tons of steel above the reflector, which is implausible. We have very light focal cabin weighting less than 50 tons. Feed cabin is supported and driven by cables and servomechanism. Inside the cabin, secondary adjustable system is mounted to compensate the offset of the cabin mainly due to wind impact.

The outstanding features of FAST and its optical geometry are shown in Figure 1. Main reflector is a spherical cap with the curvature of a 300m radius and opening up to 500m. During the observation, the 300 m illuminated area forms a paraboloid to the source direction. Feed moves on a virtual spherical cap half-way from the reflector to the origin of the sphere. The central part of a spherical surface is very nearly a paraboloid of revolution when a proper focal length is chosen. In the configuration shown in the figure, the peak deviation between deformed paraboloid (yellow dashed line) and the spherical cap will be minimized to 0.67 m within the 300 m illuminated aperture. For the maximum apparent motion of celestial objects, the rate of variation is also found to be very small, less than 0.7 mm/s, which enables a straightforward solution for the mechanical control. To deform the reflector, it is necessary to divide it into small elements. Each element is a small part of a spherical...
surface, and curvatures of all the elements are identical to get an isotropic geometry for the reflector. The main technical specifications are listed in table 1.

![Simulated image of FAST and the optics of the telescope.](image)

**Table 1. Main technical specifications of FAST**

| Specification                        | Value                                      |
|--------------------------------------|--------------------------------------------|
| Spherical reflector: Radius         | 300m                                       |
| Aperture                             | 500m                                       |
| Illuminated aperture: $D_{ill}$      | 300m                                       |
| Focal ratio: $f/D$                   | 0.4611                                     |
| Sky coverage: zenith angle           | 40                                         |
| Frequency:                           | 70MHz - 3GHz                               |
| Sensitivity (L-Band): $A/T$          | ~2000, system temperature $T_{sys}$ ~ 20K |
| Resolution (L-Band): $\theta$       | 2.9'                                       |
| Multi-beam (L-Band): beam number     | 19                                         |
| Slewing time:                        | <10 minutes                                |
| Pointing accuracy:                   | 8"                                         |

**2. Technical plan - critical technologies**

The FAST site selection started in 1994 and a karst depression called Dawodang in the southern Guizhou Province was finally chosen.

![Location, original landscape, and current look after excavation of the site.](image)

Telescope construction is divided into six sub-systems, including site survey and excavation; active reflector system; feed cabin suspension system; measurement and control system; receiver and backend system; and observatory buildings.

**2.1. Site survey and excavation**
Despite of the excellent fit between the depression profile and the spherical cap model, we still need to move some one million cube meters of earth from the karst hole. A tunnel to link the sinkhole to lower depression is required in order to guarantee the safety of the telescope. As of September 2012, the site excavation and protection of the dangerous rocks and slopes are near completion. The construction of underground tunnel of ~ 1.2 km and external roads of ~4 km in the depression have been successfully completed.

2.2. Active reflector system

Most expensive part of the telescope is the main active reflector of 500 m in diameter. The whole surface is to be supported by cable network. More than 2000 actuators drive tie-down cables according to the feedback from the measuring system to deform the surface. The optimization of the element size is a trade off between accuracy and cost. The whole reflector consists of ~ 4400 triangular panels, which give an RMS error smaller than ~ 5.0 mm.

From the aforementioned description, it can be easily seen that the long-term observation process of FAST is equivalent to long-term frequent shape-changing operation. Early research results have shown that such shape-changing operation would lead to about 500MPa of stress range, which is nearly twice the industry standard. The FAST team have carried out extensive numerical and experimental investigation to decrease the stress range of the cable required and have successfully developed a new type of steel strand with ultra high fatigue resistant property. All samples have passed through $2 \times 10^6$ fatigue cycles under 550MPa stress range. Compared with full 70000 fatigue cycles required during FAST life time and the maximum demanded stress range of 450 Mpa, enough reserve has been guaranteed (Jiang et al. 2011).

The side dimension of each reflector panel is about 11m, depending on its location on the surface. Different kind of prototyping have been investigated and experimented. The final design has a surface made of the aluminum sheet, backup of aluminum spatial truss and an adjustable layer in between.

It is extremely important to have reliable actuators considering their large amount. Besides long life, easy maintainability and less dependence on neighboring ones are crucial factors. Various types of actuators have been manufactured and tested at the Miyun station of NAOC and at the depression site. The final selection between mechanical and hydraulic actuators is under way.

2.3. Feed cabin suspension system

Feed cabin suspension system might be the most risky part of FAST. There is no solid connection between the reflector and the feed cabin because of the large dimension of the telescope. The feed cabin of FAST is supported and driven by cables and servomechanism. Inside of the cabin, secondary adjustable system is employed to achieve the required accuracy. The designs consist of three essential parts, including the cable network that supports and drives the feed cabin, the secondary adjustable devices inside the cabin that carry the most precise part of the receivers, and the close loop control. Numerous models were made to verify the feasibility of the concept. Because of the large dimension and the complicated dynamics, similarity laws may not guarantee applying the results from down-scaled models to real structure. The team has carried out end-to-end simulation cooperated with MT Mechatronics and Technical University Darmstadt. This analysis has confirmed the feasibility of the concept and yielded critical results for system optimization. The displacement of feed cabin after first adjustment control can be constrained to be within a few centimeters. The achievable accuracy of feed position with the help of the secondary stabilizer turns out to be a few millimeters, which meets the requirement of telescope pointing.

The detailed design and manufacture have started in a Chinese lift firm. The detailed design for 6 suspension towers higher than a hundred meters has been finished and the groundwork has begun. Preliminary design for feed cabin has completed, and detailed design and construction started to accept bids.

2.4. Measurement and control system
Major parts of FAST are active, that requires fast and high accuracy measurement and control in long distance. One heavy task is the control of 3-D positions and orientation of focus cabin which need high accuracy ~ 2 mm, sampling rate > 10 Hz in a large working range up to 300 m. Another one is the control of the profile of main reflector, surveying ~1000 nodes in illuminated area in real time within a interval of a few minutes.

The datum lines have been established, monitoring shows the accuracy and stability better than 1 mm. Complex control network underneath the reflector is at the concept design stage, dividing the ~2400 actuators into districts and groups. Most challenging issue would be the EMI from active equipments over the depression.

2.5. Receiver and back-end system
FAST will build eight sets of receivers, covering a frequency range of 70MHz-3GHz. Scientific back-ends, time and frequency standard, monitoring/diagnostics of the receivers have been optimized through long term international cooperation. The 19-multi-beam receiver at L-band is the core receiver system of FAST. A trilateral collaboration among NAOC, JBCA and CSIRO has been established for a designing study of this important receiver.

L-band single pixel receiver has been developed in FAST lab, covering a wide band 1.1 – 1.9 GHz with return loss better than -22dB and RL isolation < -22dB across the band. We are now working on the feasibility of using honeycomb and carbon fibre material to reduce the weight, therefore reduce the load on the stabilizer in the cabin.

3. FAST Sciences
FAST should have significant impact on astronomy and has the potential to revolutionize other areas of the natural sciences. Its unique contributions to science may not yet be predictable at present. Major key scientific projects are planned (Nan et al. 2011)

- survey the Galactic ISM in HI at a resolution comparable to the current large scale CO surveys;
- discover ~ 4000 new Galactic pulsars and search for the first extragalactic pulsars beyond Magellanic clouds;
- detect hundreds of thousands of HI galaxies and detect individual massive galaxies up to z ~ 1;
- spectroscopic survey of rich Galactic sources with continuous coverage between 70MHz and 3GHz;
- join the international VLBI experiments
- search for radio signals from exoplanets
- SETI

During the early stages of telescope adjustments, we could start from low frequencies. Two receivers are planned for early sciences. One is the 7- multi- beam receiver with an operating band 400MHz-560MHz; and another single pixel 270MHz-1450MHz. These receivers will be used for low frequency deep pulsar survey in the Milkyway and nearby galaxies, for searching for large molecules in Orion nebula, for studying HI distribution of nearby disk galaxies, e.g. M31 and M33, and for detecting distant OH mega-masers.

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