Performance overview of the Five-hundred-meter Aperture Spherical Telescope (FAST)

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Abstract：

We give a brief introduction of current FAST performance, available observational modes and status of the receivers and backends, aiming at providing a reference for commissioning and time allocation of early science observations of FAST in the coming year. This document will be updated along with the progress of the FAST commissioning.

1. Introduction of FAST

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is a Large Science and Technology Foundation Development Project in the national "11th Five Years Plan". The construction of the telescope was completed on Sept 25th, 2016. Since then, it has been in the commissioning and scientific verification stage.

After ~2 years commissioning, FAST has met most of its design and is nearly ready for the national project review, which expected to be in Sept 2019. The basic specifications of FAST are listed in the following table. More details will be given in the following sections.

Specifications of FAST（commissioning Phase）

Coordinates：	Longitude	106°51' 24.0"E
	Latitude	25°39' 10.6"N
	Altitude	1110.0288 m
Primary Dish：	Aperture	～500m
	Radius	～300m
	Illuminated Aperture	300m
	Surface Accuracy	～8mm（rms）
	Opening Angle	110 -120°
Focal Length：		～139 m
Focal Ratio：		0.46 - 0.47
Sky Coverage：		40°
		-14.6°< Dec < 65.6°
Frequency Coverage：		70 MHz - 3 GHz
Wavelength Coverage：		4.3 m - 10 cm
Angular Resolution（FWHM）：		2.9' (L band)
Sensitivity（L band）		A/T ~ 2000m^2/K
		System Temperature～25 K
Polarization		Full Polarization（circular or linear）

Pointing Accuracy:	16"
Slewing time:	< 20 min

The following is a picture of the central control room of FAST. For most observation modes, 5-7 operators are on duty.

Figure 1.1 Layout of Central Control Room

2. Receivers

FAST is equipped with 7 independent receivers, covering from 70MHz – 3000 MHz. Among them, one is the L-band 19-beam Receiver, and the other 6 are single beam receivers. Their specifications are listed in the following table.

Because of the weight and volume limitations, these receivers are coupled with 3 sets of working platforms, and cannot be installed on the focus cabin simultaneously. Depending on the weight and size, it may take 2-5 days to switch receivers.

All receivers are of linear polarization design. Circular polarization signals can be obtained through backend.

FAST Receivers

Receiver	Frequency Coverage [MHz]	Aperture [m]	FWHM [arcmin]	T_{sys} [K]	Sensitivity [K/Jy]	Polarization [l]	Bandwidth [MHz]
19 Beam	1050 - 1450	300	2.9 [1.4 GHz]	< 25 K	16.0	38 × L	400
B01	70 - 140	--	--	< 1000 K	--	2 × L	70
B02	140 - 280	--	--	< 400 K	--	2 × L	140
B03	270 - 1620	300	--	< 120 K	--	2 × L	1350

B04	560 - 1020	--	--	< 60 K	--	2 × L	460
B05	1100 - 1900	--	--	< 25K	--	2 × L	800
B07	2000 - 3000	--	--	< 25K	--	2 × L	1000

2.1 L-band 19-beam Receiver

The L-band 19-beam Receiver was manufactured by CSIRO in Australia. Its working frequency range is 1.05 - 1.45GHz, and measured system temperature is ~18K.

The L-band 19 Beam Receiver is currently the major receiver. Unless for very important and urgent science tasks, it will be the only receiver used by FAST in 2019.

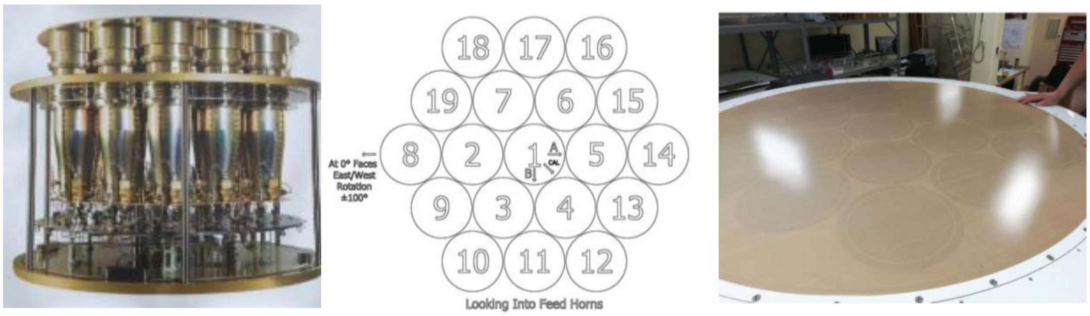


Figure 2.1 The L-band 19 Beam Receiver.

There is two level for noise calibration signal (CAL), high power noise and low power noise. CAL of the 38 polarizations are generated by power splitting of one noise source. As shown in the following figure, the high power noise has a T_{cal} of ~12K, and low power noise has T_{cal} ~1.2K, only ~1/10 of that of high power noise.

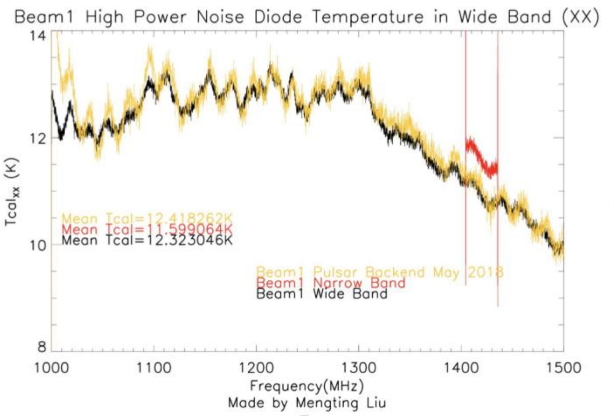


Figure 2.2 (Central beam) Input noise signal T_{cal}（high）varies with the frequency. Lines with different colors represent results obtained using different output modes and

different bandwidths.

2.2 Wideband Receiver（270-1620MHz）

The Wideband Receiver was built in collaboration with Caltech. It has the working frequency range of 270-1620MHz, and measured system temperature of ~50K. Because of the wide bandwidth, the parameters vary with frequency within the bandpass.

From July 2016 to May 2018, before the L-band 19 Beam Receiver being installed, FAST was using the Wideband Receiver for many observations, including those leading to the discoveries of more than 40 high quality pulsar candidates.

Fig 2.3 Wideband Receiver

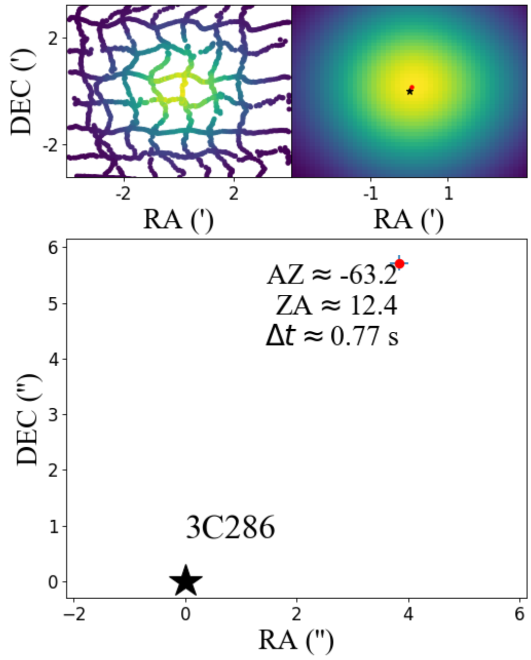
2.3 Other Receivers

The other receivers are not commissioned yet. Because it is very complicate to install or de-install the L-band 19-beam Receiver, it will be always placed on the lower-platform and will not be replaced by any other receivers in the future 1-2 years, unless there is some particular scientific reason to do otherwise.

The 70-140MHz Receiver can be installed underneath the L-band 19 Beam Receiver. There is a plan of constructing a temporary platform under the 19-beam receiver for testing of other receivers. It be available in a few month.

3. Pointing Accuracy

After calibrations, the pointing accuracy of FAST has reached 15” . The following figure present some scan testing examples.



We are currently doing more tests to check the dependence of the pointing accuracy on the pointing direction and elevation, though according to the theory, the dependence should be minimal.

4. System Temperature

When the L-band 19-beam Receiver is pointing to zenith, the system temperature is about 18K. When the zenith angle is larger than 26.5° , the system temperature increases rapidly. At zenith-angle = 40° , the real system temperature can be as high as ~30K, depending on the frequency.

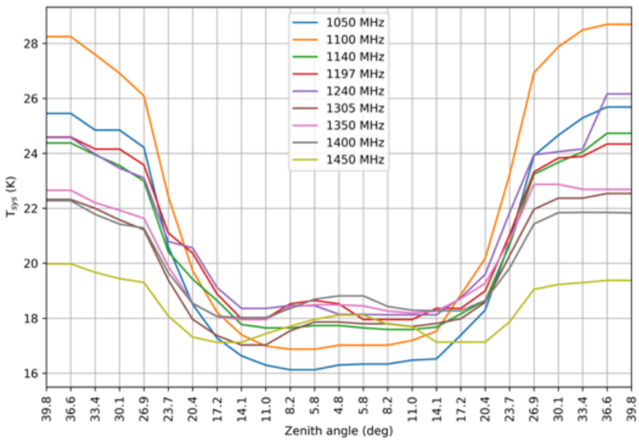


Figure 4.1 (Central beam) Dependence of T_{sys} on Zenith angle. Lines of different colors represent measurements at different frequencies. Observation target: 3C286.

5. Sensitivity

The measured sensitivity of the L-band 19-beam Receiver is 2500m^2/K for small zenith angles. Because of the system temperature increased by ground illumination, the sensitivity decreases at large zenith angles. It is recommended that, in order to get optimal results, the target should be at zenith-angle < 30° .

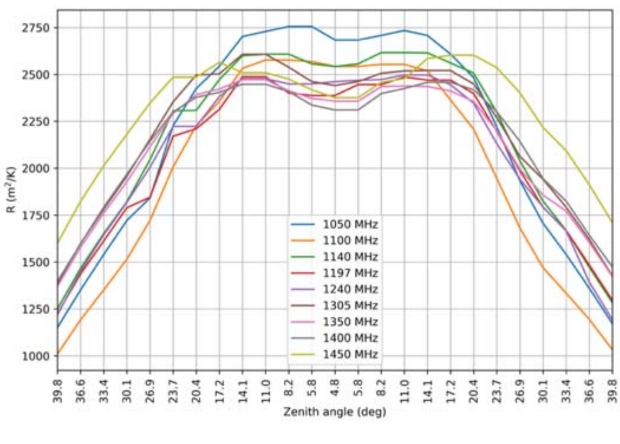


Fig 5.1 FAST sensitivity with 19-beam Receiver (Central beam). Observation target: 3C286.

6. Efficiency

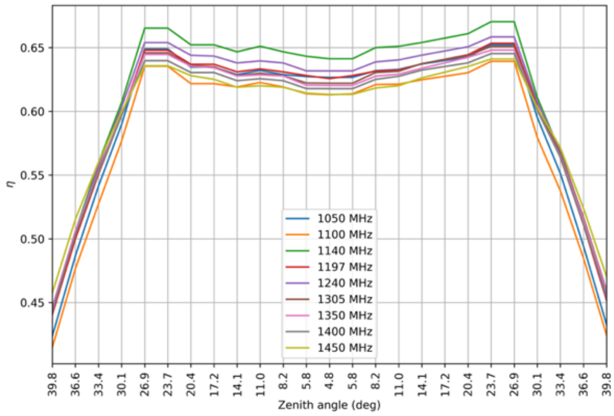


图 6.1 Dependence of the efficiency on zenith angle, measured by multiple observations. The rapid decrease of the overall efficiency near the two ends is due to the size of the illuminated aperature becoming less than 300 meters.

7. Signal Flow Chain

FAST uses optical fibers to transfer signals. For receivers with working frequency lower than 2 GHz, RF signals are transmitted to backend room directly. No IF signals and no local oscillator. Therefore these receivers do not have frequency switching mode.

8. Time System

FAST uses the GPS time service, with a hydrogen maser clock for local reference clock. Differences between GPS and the hydrogen maser are recorded and kept for. This can be used to recover precise timing if needed. The time system accuracy for pulsar observations is better than 50ns. The specifications of the time system are better than the requirements for spectral line observations.

9. Backends

FAST has 5 back-end systems for different categories of astronomical observations. They include: spectral line, pulsar, VLBI, SETI, and the data process and stoorage system. Their specifications are listed in the following table.

Available Backend Systems

Back-End	Bandwidth (MHz)	Sampling (μs)	pol	stokes	IF	channels	Format
ROACH2 (Spectral line)	Whole Wide Band Mode 500	1006632.96 (～1s)	2	Full or 2 polarizations (XX、YY)	1	1024k / 64k	fits
	Narrow Band Mode 31.125	1006632.96 (～1s)	2	Full or 2 polarizations (XX、YY)	1	64k	fits
ROACH2 (Pulsar)	500	49.152 / 196.608	2	Full or 2 polarizations (XX、YY)	1	4k	fits
CRANE (Spectroscopy)	31.25 × 4 ~ 200MHz --1.7GHz		2	Full	4	65536 (64k)	fits
CRANE (Pulsar)	2 GHz	64 us	2	Full		8192	fits
VLBI	--	--	--	--	--	--	--
SETI	--	--	--	--	--	--	--

Because the backends have many modes and the commissioning are very complicate, we have so far commissioned only the modes that are used most frequently. Here is a brief description:

- The 19-beam receiver uses 12 roach terminals, including 10 on-line and 2 backups. Among the 1^{st} – 9^{th} roach, each takes data from two beams. The 10^{th} takes data from only one beam. Altogether, they take data from the 19 beams.
- The spectroscopy and pulsar modes can work simultaneously. A new mode that have high frequency calibration signals is under development.
- Spectral line data are in 32bit SDFITS format. Pulsar data are in 8bit PSRFITS format.
- The pulsar mode has the minimum sampling time of 8.192 μs, while usually the sampling time is set at 49.152 μs. The restriction is mainly due to limited storage.
- ROACH2 has 500MHz bandwidth cope with the 19-beam receiver. It is slightly wider than the working frequency range of 1050-1450MH in order to leave space for aliasing.
- The back-ends for SETI and VLBI are still under commissioning. They are not available for normal observations yet.
- CRANE terminals are usually only for special modes. It is recommended that most observations use ROACH2 backends。

10. Standing Wave

Progress has been made in shielding, which improved the situation for the standing wave. As shown in the following figure, now the standing wave has amplitude of ~ 0.2K and frequency ~1MHz, likely from between the feed cabin and the reflection surface. It will affects the extragalactic observations. We are still working on minimizing the standing wave.

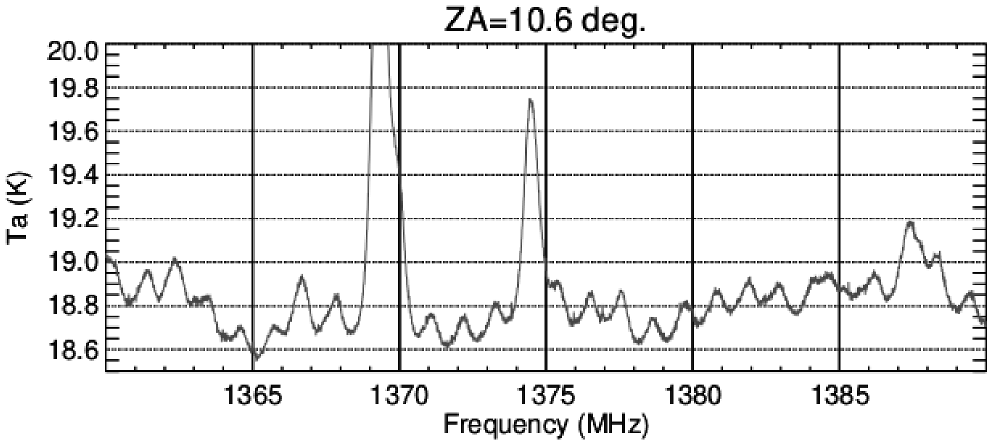


Figure 10.1 Sample plot for standing wave.

11. Observation Modes

Four observation modes are now available:

Mode 1: Drift Scan Mode

This is currently the major mode, mainly for pointing calibration and pulsar searching observations. It has produced most data, working mainly in nights.

Mode 3: Tracking Mode

FAST can track targets as long as 6 hours. For most targets, the maximum tracking time is 4 – 6 hours, depending on the sky position. As shown in the following figure, the maximum tracking time is significantly reduced when sources are too much in the south or north.

Because the FAST is still in the commissioning phase, we don't recommend tracking observations with zenith angles > 30° for safety.

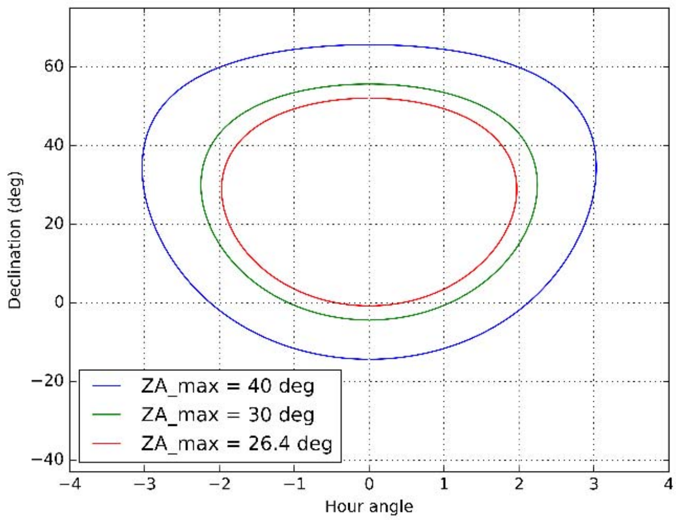


图 11.1 Plot of maximum tracking time.

Mode 4: Basket Waving Mode

This mode has not been fully tested, is not available yet.

Mode 5: On the Fly Mapping Mode

This is mainly for imaging and pointing test observations. Has been tested thoroughly. Recommend to use.

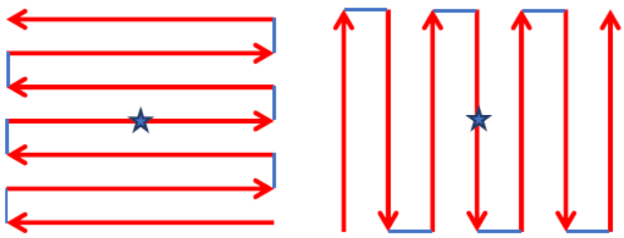


图 11.2 Illustrative plot for raster scan mode.

Originally, slewing was Mode 2. Now slewing do not need a dedicated command. It is automatic by the system. It takes maximum 20 minutes to slew to a new source, and the closer the target the less time needed.

Because FAST is different from traditional telescopes, it is not very efficient in slewing. New methods are being investigated to alleviate this issue. Other modes for such as standing wave removal, planets and comets observations, etc., are also in development.

12. RFI Situation

FAST is in a rather good electromagnetic environment. Major RFI sources include: signals from public TV stations, FM radio stations, airplanes, cell phone stations, and satellites. The frequency bands for FM radio and cell phones cannot be used for observations. The other RFIs occur mostly only in short periods.

There are already a large amount of monitoring data for this, though they have not been put into a unified system. In near future, we plan to provide an web interface for RFI data.

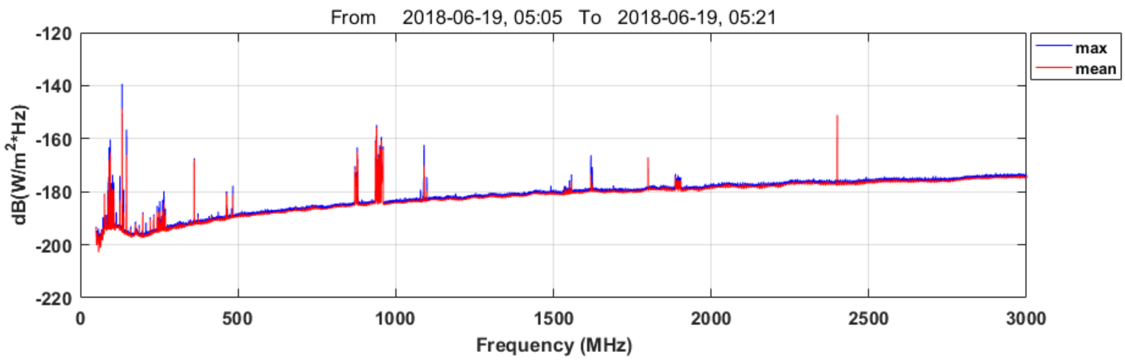


图 12.1 A plot of signals within the entire frequency range of FAST.