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FAST VLBI: current status and future plans

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Abstract The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the largest single-dish radio telescope in the world, and is now being commissioned after the first light in September 2016. Very long baseline interferometry (VLBI) is among the key science topics according to the original design. The FAST VLBI system has been established, and the first VLBI fringe has been successfully obtained. FAST will significantly improve the sensitivity of the existing VLBI networks in the future, and some science projects in need of high sensitivity will benefit from its participation.

Key words: instrumentation: interferometers — telescopes — site testing

1 INTRODUCTION

The construction of the Five-hundred-meter Aperture Spherical radio Telescope (FAST) has been completed and it entered the commission phase in September 2016. This astronomical instrument has since progressively shown its outstanding abilities from the preliminary measures, with several indices of performance better than expected (Jiang et al. 2019; Lu et al. 2019a,b; Yu et al. 2019).

Very long baseline interferometry (VLBI) is a type of interferometry that is used in radio astronomy, where the voltage signals from widely separated telescopes are recorded before transmission to a central correlation. VLBI is best known for imaging distant radio sources, spacecraft tracking, and for applications in astrometry, due to its ability to achieve the highest space resolution, which is determined by the maximum separation between the telescopes.

Like other big radio telescopes in the world, VLBI was listed as one of the key topics of FAST from its inception (Nan et al. 2011). After final testing in the near future, FAST will be expected to contribute its significant ability to the VLBI networks.

Here, we briefly introduce the current status and future prospects of FAST VLBI. The FAST VLBI system and VLBI fringe experiment are described in Section 2. The VLBI ability of FAST and possible benefit for the VLBI networks are discussed in Section 3. VLBI scientific projects, including pulsar astrometry and distant quasi-stellar objects (QSOs) are presented in Section 4. Future plans are written in Section 5. A summary is given in Section 6.

2 FAST VLBI SYSTEM

2.1 Instruments

The FAST VLBI system basically includes the telescope with receivers and the backends including the time/frequency system, the terminal, and the data recording system.

There are seven sets of receivers for FAST (Table 1), which will all be available for the VLBI observation. Except for the two sets of low frequency receivers, the other five sets of receivers are all cryogenically cooled. Two sets of receivers have been mainly used and comprehensively tested in the commissioning of FAST. Dozens of new pulsars have been discovered with the low-frequency, ultra-wideband receiver (frequency range from 0.27 to 1.67 GHz) (Smith & Weinreb 2016; Jiang et al. 2019). The 19-beam receiver installed in July in 2018, will be used for the survey project CRAFTS[1] (Li et al. 2018).

[1] The Commensal Radio Astronomy FAST Survey

Fig. 1 The 19-beam receiver, with frequency range of $1.05 - 1.45$ GHz, is installed on the lower platform of the Stewart manipulator (Stewart 1965; Yao et al. 2019), surrounded by the radiation shielding fabric.

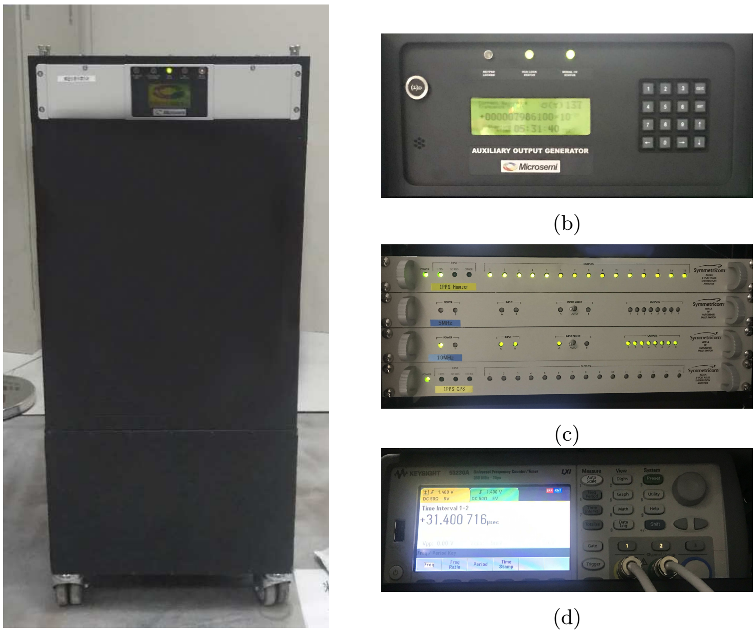

Fig. 2 The time/frequency system of FAST. (a) Hydrogen maser. (b) Auxiliary output generator. (c) Pulse distribution amplifiers for hydrogen maser and GPS. (d) Time/frequency counter.

The time/frequency system (Fig. 2) includes the hydrogen maser and auxiliary output generator from the Microsemi company (a subsidiary of Microchip Technology inc) located in California, providing the precise time/frequency. Its stability[2] can reach 1.5×10^{-15} in 10 000 seconds (from the datasheet of Microsemi MHM 2010); pulse distribution amplifier; the Global Position System (GPS), providing the pulse-per-second (1PPS) signal; and the time/frequency counter for the time interval between the H-maser and GPS.

ROACH2[3] (a stand-alone FPGA[4] board developed by the CASPER[5]) is used for pulsar, spectral line and Search for Extra-Terrestrial Intelligence (SETI) observations, and will be also used for the FAST VLBI observations. The

[2] Allan deviation measured in 0.5 Hz bandwidth

[3] Reconfigurable Open Architecture Computing Hardware

[4] Field Programmable Gate Array

[5] Collaboration for Astronomy Signal Processing and Electronics Research

Table 1 Seven Sets of Receivers at FAST

No	Band (GHz)	Beams	$T_{\rm sys}$ (K)	Cyro.
1	0.07–0.14	1	1000^a	No
2	0.14–0.28	1	400^a	No
3	0.27–1.62	1	$<39^b$	Yes
4	0.56–1.02	1	60^a	Yes
5	1.15–1.72	1	25^a	Yes
6	1.05–1.45	19	$<25^c$	Yes
7	2.00–3.00	1	25^a	Yes

[a]Nan et al. (2011); [b]Smith & Weinreb (2016); [c]Jiang et al. (2019). All bands have right- and left-handed circular polarizations (RCP, LCP) receivers.

VDIF (VLBI Data Interchange Format) data is output from the ROACH2, after the radio frequency (RF) signal is high speed A/D converted and directly sampled (Jiang et al. 2019).

Mark VI (developed by the Haystack Observatory) is used as the VLBI data recording system, which is available for the 16 Gbps VLBI observation. There are four disk modules, each of which consists of eight 8-TB disks. The total storage is 256 TB, which is used to record the VLBI data.

2.2 VLBI Fringe Experiment

After the VLBI system has been established, the VLBI fringe is the convinced mark for the VLBI ability of FAST. On 2019 January 24, the first VLBI fringe between FAST and the Tianma 65-m telescope was successfully obtained at L band. The experiment was performed with the central beam of the 19-beam receiver of FAST (Fig. 1), and the compact QSO of 3C454.3 with flux of about 14 Jy at 1.4 GHz (White & Becker 1992; Cooper, Lister & Kochanczyk 2007) was selected as the target. The spheric centre was chosen as the reference point, the coordinates of which are $\rm N25^\circ39'10.626537''$ in latitude, $\rm E106^\circ51'24.00074''$ in longitude, 1110.02881 m in sea surface height. To conduct the experiment easily, the duration of each scan was set to be 55 seconds. With the inputs of locations and time intervals between the clocks, the fringe (Fig. 3) was obtained in short time with the DiFX[6] correlator at the Shanghai Astronomical Observatory (SHAO). This is a milestone for the FAST VLBI system.

3 VLBI BENEFIT WITH FAST

As the biggest single-dish radio telescope in the world, FAST would significantly increase the capability of the current VLBI networks (Zhang 2017). FAST is located far from the telescopes in Europe, and can provide more sensitive long baselines for the EVN[7] (Fig. 5). The sensitivity of EVN observations could be much improved with FAST. For a typical 2.5 hours EVN observation, the sensitivity could be improved as factor of two if FAST can contribute more than 80 minutes observing time. FAST has about 2 times the collecting area of the Arecibo Telescope (AO), and substituting FAST for AO would increase the signal-noise ratio by $\sim 50\%$ on any EVN observation at L band.

Compared with the former biggest single-dish telescope, the AO, FAST is not only larger in the collecting area, but also in sky coverage. The maximum zenith angle of FAST is 40 degree (the sensitivity ($A_{\rm eff}/T_{\rm sys}$) decreases gradually as the zenith angle when ZA$> 20.4^\circ$ and the sensitivity at ZA $= 40^\circ$ is half of that at ZA $< 26.4^\circ$, Jiang et al. 2019), 2 times larger than that of the AO. For sources with declination from 0 to 60 degrees, FAST can contribute more than four hours of tracking time (Fig. 4).

4 VLBI SCIENTIFIC PROJECTS

The biggest advantage of FAST joining a VLBI network is to improve its sensitivity, which could bring more opportunities in VLBI science. Observing important weak targets would have the high priority for FAST VLBI observation, such as pulsars (astrometry) and distant QSOs.

4.1 Pulsar Astrometry

Because pulsars are the excellent laboratories for some of the most extreme physics in the universe and their research usually relies on the sensitive radio instruments, pulsars are one of the key science topics of FAST, and more than 50 new pulsars have been discovered by FAST in the past two years (CRAFTS[8], Li et al. 2018).

Many scientific questions are related to the distances of pulsars, such as the correction of radio luminosity, the constraint of size of the neutron star photosphere. Most pulsar distances have been estimated from the dispersion measures (DM) and an electron density model of the Galaxy (Taylor & Cordes 1993; Yao, Manchester & Wang 2017). Pulsar timing can provide more accurate estimate of the parameters. However, pulsar timing requires frequent observations over a long period (Deller 2009). Pulsar astrometry is a model independent method to get the precise values of these fundamental parameters (positions, proper motions, distance, transverse velocity, etc.), which could be obtained within a few years (Deller 2009; Deller et al. 2018).

As a pilot project, we selected three FAST-discovered pulsars, with higher flux density and suitable phase reference sources. In order to propose the EVN observation at L band, we observed them with the 19-beam receiver to get

[6] Distributed FX-style software correlator

[7] The European VLBI Network

[8] `http://crafts.bao.ac.cn`

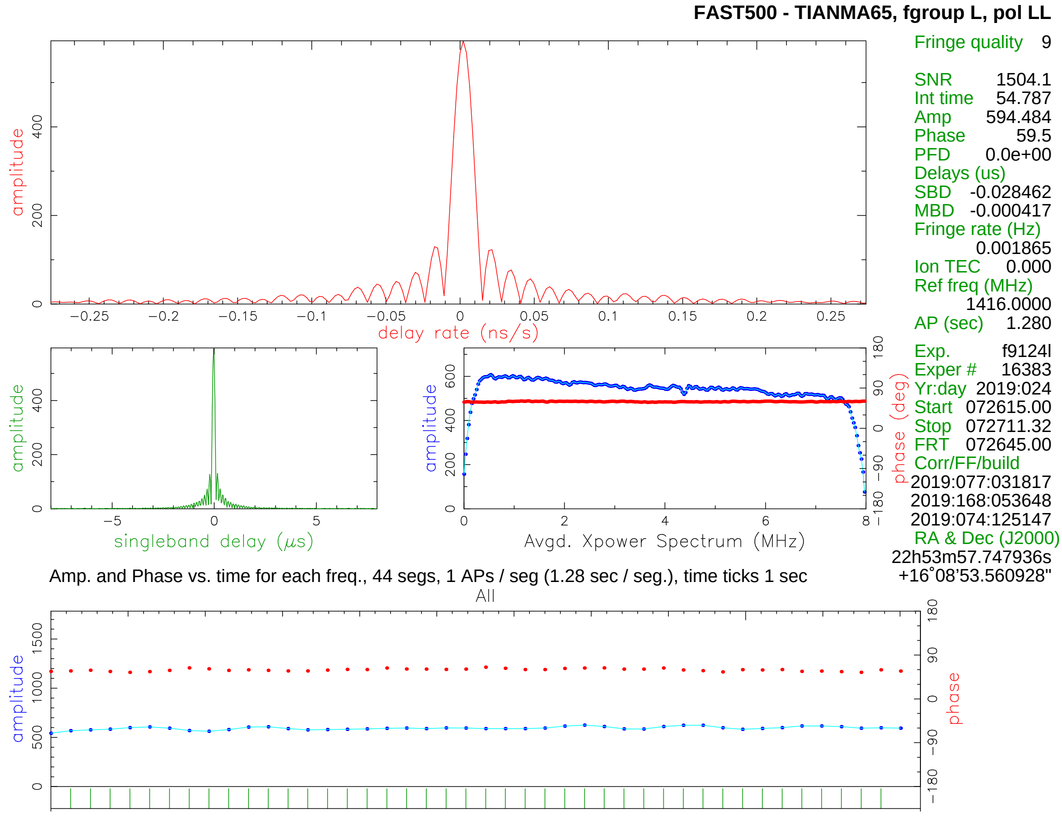

Fig. 3 The first fringe between FAST and Tianma 65-m telescope. The signal-to-noise ratio (SNR) is 1504 with an integration period of 55 seconds, and the amplitude and phase are extremely stable during the 55-second scan. The bottom panel shows the fringe amplitude (*blue*) and phase (*red*), which are steady at ~ 600 and 60^o, respectively.

better coordinates and the lower limits of their flux density. We proposed the phase referencing EVN observations for these three pulsars. For VLBI phase referencing, the astrometry accuracy is dependent on the separation between the target and reference source (Deller et al. 2018). The closest calibrators are chosen for these pulsar candidates, while the in-beam calibrators are also needed. Two-hours e-EVN observations (code RSC04) have been granted by the EVN PC to test if these in-beam NVSS[9] sources are compact to be the in-beam calibrators. The formal EVN proposal received a high rating and is expected to be scheduled soon. The immediate goal of this pilot project is to determine accurate positions of these three pulsars, and the final goal is to measure their parallaxes and proper motions, which will require several epochs of EVN observations.

As the CRAFTS proceeds, the number of new FAST pulsars will increase rapidly, and there will be more pulsars suitable for the VLBI astrometry, especially after FAST formally joining the VLBI network in the future, which will increase the number of sensitive baselines and the ability to observe weaker pulsars.

[9] the NRAO VLA Sky Survey

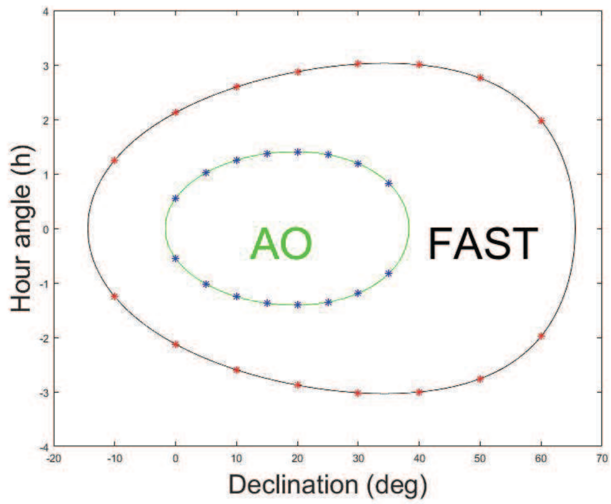

Fig. 4 Tracking time for objects at different declinations, FAST vs. Arecibo telescope (AO).

4.2 Distant QSOs

Quasars, also known as QSOs, could provide important informations of the evolution of the active galactic nucleus (AGNs) and growth of the central supermassive black holes (SMBHs) in the early universe (Jiang et al. 2016).

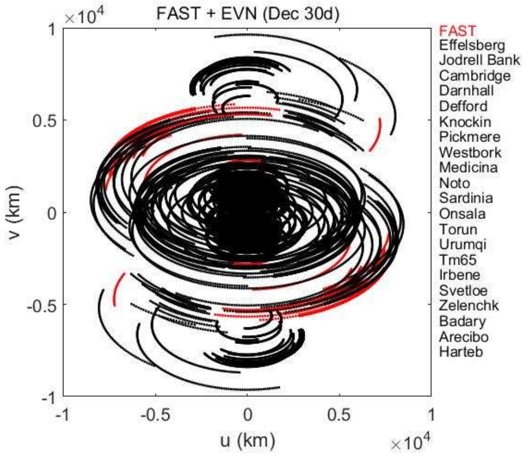

Fig. 5 EVN projected baseline (uv) plot at L band for an object at Dec. 30°, with FAST baselines in *red*.

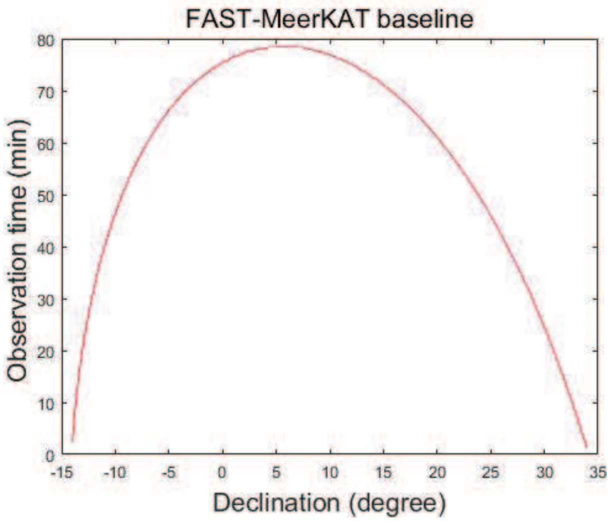

Fig. 6 Shared observing time between FAST and MeerKAT.

Distant QSOs are usually weak in radio due to their high redshifts. There are about 200 known quasars at redshift $z > 5.7$ from the million quasar catalogue (MILLIQUAS, version 5.2, Flesch 2015), and only 12 of them (6%) are detected in the radio surveys, such as NVSS (Condon et al. 1998), FISRT[10] (Becker, White & Helfand 1995) and SUMSS[11] (Mauch et al. 2003). So far, only several $z \sim 6$ radio quasars have been observed with VLBI (Momjian et al. 2008; Frey et al. 2008, 2011; Cao et al. 2014; Lobanov et al. 2015) and their steep radio continuum spectra ($\alpha \sim -0.5$) and compact radio structure ($< 100\,$pc) show they are similar to gigahertz-peaked-spectrum (GPS) or compact-steep-spectrum (CSS) sources. Identification of more distant QSOs are needed to show if most of the high redshift radio quasars are young radio sources in the early Universe. Besides, surface brightness derived from the observations are useful to testify if the high-redshift sources are AGNs (Cao et al. 2014).

As a pilot project, we selected three distant QSOs, J0903+5012 ($z \sim 6.31$), J0020+3021 ($z \sim 6.2$) and J1250+4818 ($z \sim 6.2$), with flux density larger than 6 mJy at 1.4 GHz. We proposed the EVN observations at L band to study their radio structures and surface brightness. Multi-wavelength (1.6 GHz, 5 GHz and 8.3 GHz) observations are needed to study their spectra (Frey et al. 2008; Coppejans et al. 2016). Phase referencing observations are also needed, and the closest calibrators are selected for these QSO candidates.

If the pilot project goes well, we plan to observe more distant QSOs, especially when FAST joins the VLBI networks in the future.

5 FUTURE PLANS

We will continue the FAST VLBI experiments during the commissioning. Fringe experiments would be conducted with other radio telescopes, such as the 26-m telescope of Xinjiang Astronomical Observatory (XAO), to improve the FAST VLBI system.

Experiments between FAST and international radio telescopes are also necessary, so as to test the ability of FAST to join the current VLBI networks (EVN, LBA etc.). Recently, the MeerKAT telescope (precursor of the SKA1-MID) from South Africa achieved its VLBI fringes with the EVN stations Effelsberg (Ef) and Hartebeesthoek (Hh) in 2018. For candidates with declination from $-5°$ to $+20°$, the FAST-MeerKAT baseline could be available for more than one hour (Fig. 6), which makes the cooperation between FAST and MeerKAT possible. If experiments or observations could be conducted between MeerKAT and FAST, then it would be meaningful and helpful to build a cooperation between FAST and SKA1-MID in the future.

Longer fringe experiments are needed to fully characterize the phase stability. In addition phase-referencing mode will be established to observe the weak sources. Moreover, softwares to control the VLBI backends and the Mark 6 are under development to facilitate the automatic VLBI observations. Some new instruments will be installed, such as a set of backend DBBC2[12], to allow FAST to be involved in the VLBI networks more easily.

6 SUMMARY

The viability of FAST as a VLBI station has been established, and the first VLBI fringe has been obtained between FAST and the Tianma 65-m telescope, which is a milestone for FAST VLBI. FAST would significantly improve the sensitivity of VLBI networks, and some scientif-

[10] Faint Images of the Radio Sky at Twenty-centimetres

[11] The Sydney University Molonglo Sky Survey

[12] Digital BaseBand Converter 2

ic projects in need of high sensitivity will benefit from its participation in the VLBI observations.

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