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HI Surveys with FAST and ASKAP

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Abstract

Surveys of galaxies in the 21-cm line of neutral hydrogen are important parts of the science case for the Five-hundred-metre Aperture Spherical Telescope (FAST) and the Australian SKA Pathfinder (ASKAP). The FAST strawman design with 19 beams and low system temperature allows a "survey speed" comparable to that of ASKAP. The combination of the two telescopes will allow a shallow all-sky survey of over 10^6 galaxies south of about declination 56^o. However, the weight limit for the strawman FAST receiver imposes a low-frequency cutoff of about 1.23 GHz (as for the Parkes multibeam design), corresponding to a redshift of 0.16 above which multibeam observations are not possible. To better facilitate deep observations with FAST, and better complement ASKAP surveys, I explore an alternate scenario of a 7 beam FAST design capable of both shallow and deep HI surveys over a wider frequency range.

1. Introduction

The Five-hundred metre Aperture Spherical Telescope (FAST), to be located in Guizhou province, China, will be the world's largest radio telescope until the Square Kilometre Array (SKA) is built (Nan et al. 2002). It is modelled on the Arecibo reflector, with innovations which allow it to have a larger focal plane (wider field of view) and a wider sky coverage. The science goals include pulsar astronomy (Nan et al. 2006) and extragalactic 21-cm hydrogen-line surveys (Duffy et al. 2008). The Australian SKA Pathfinder (ASKAP), to be located at the Murchison Radio-astronomy Observatory (MRO) in Western Australia, will be one of the world's fastest survey radio telescopes at frequencies around 1 GHz until the SKA is built (Johnston et al. 2007).

21-cm surveys with FAST and ASKAP will be an excellent way studying galaxies in the nearby Universe in a similar manner to that achieved by recent optical surveys such as 2dFGRS, SDSS and 6dFGS (Colless et al. 2001, Jones et al. 2005). The declination ranges are complementary, and similar redshift ranges will be probed, which will allow multi-wavelength comparisons of the properties of large samples of galaxies across both hemispheres. The key science goals include large-scale structure, gas evolution, environmental dependence of the HI mass function and cosmology (Johnston et al. 2007, Duffy et al. 2008).

Unlike for the SKA, the achievement of the key science goals for FAST and ASKAP requires long integration times, of the order of a year. FAST has a relatively small field-of-view; ASKAP has a relatively small aperture. However, the survey speed[1] of the two telescopes is remarkably similar. The ASKAP 'expansion' option (Johnston et al. 2007) is 1.7 times faster than the FAST strawman design at 1.3 GHz (z=0.09); the ASKAP 'strawman' design is 2.7 times slower than FAST strawman design at 1.3 GHz. Although, the exact design goals of each facility is still being discussed, both facilities are funded, so the final specifications are not expected to be vastly different from that summarised in Table 1.

Instrument	D	ε	T (K)	Beams	Ω (deg^2)	Survey Speed	Beams	Ω (deg^2)	Survey Speed
				1.3 GHz			0.8 GHz		
ASKAP									
1. strawman	30x12m	0.8	50	30	30	1.0	30	30	1.0
2. expansion	45x12m	0.8	35	30	30	4.6	30	30	4.6
FAST									
1. strawman	500m	0.2	20	19	0.062	2.7	1	0.009	0.4
2. wideband	500m	0.2	20	7	0.023	1.0	7	0.060	2.6

Table 1: Estimated survey speed for ASKAP and FAST at two frequencies: 1.3 and 0.8 GHz. The two ASKAP realizations refer to the strawman and expansion options of Johnston et al. (2007). The FAST strawman option refers to the current FAST design with 19 beams, but only above 1.23 GHz (Nan, private comm.); the FAST wideband option is a suggested option with only 7 beams, but extending to lower frequencies. The symbolic column headings refer to telescope diameter (D), aperture efficiency (ε), system temperature (T) and field-of-view (Ω). Some parameters for FAST (ε,Ω) were scaled from the Parkes multibeam specifications, assuming an illuminated diameter of 300 m.

In Table 1, it is apparent that both ASKAP realizations are substantially faster than FAST at 0.8 GHz. This is because weight restrictions make it difficult the extend the 19-beam design of FAST below 1.23 GHz (Nan, private comm.). I therefore explore an alternative possibility for FAST – that of wideband 7-beam design which extends to lower frequencies (FAST wideband option 2 in Table 1). The advantage of such a design is a better match to the ASKAP mapping speeds and a much better ability to explore evolution in the properties of galaxies at redshifts above 0.16.

For both facilities, several different types of HI surveys will probably be required in order to realize the various science goals. I broadly characterise these surveys into two classes: (1) 'all-sky' shallow surveys; and (2) deep surveys of small regions of sky. For each of these types of survey, I look at the relative performance of both FAST and ASKAP realizations.

[1] Survey speed is approximately proportional to $(\varepsilon A/T)^2\Omega$ where εA is the effective telescope collecting area, T is the system temperature and Ω is the field of view.

2. Shallow Surveys

Shallow surveys with FAST and ASKAP are the quickest way of obtaining large samples of galaxies in HI. Such surveys are almost a pre-requisite for instruments with vastly improved capabilities compared with their predecessors. They will allow the discovery of unusual objects of low mass in and around the Local Group (Staveley-Smith 2008), probe large-scale structure of gas-rich galaxies in the local Universe, including behind the plane of the Milky Way, and provide a useful probes of cosmological parameters complementary to existing optical surveys (Johnston et al. 2007, Duffy et al. 2008).

The simulated redshift distributions for putative 1-yr shallow surveys with FAST and ASKAP are shown in Figure 1. As also indicated in Table 1, the performance of the instruments is fairly similar. The FAST strawman design will detect around 840,000 galaxies above an HI mass of 10^6 $M_{\odot}$; the ASKAP strawman (expansion) design will detect 580,000 (1,700,000) galaxies.

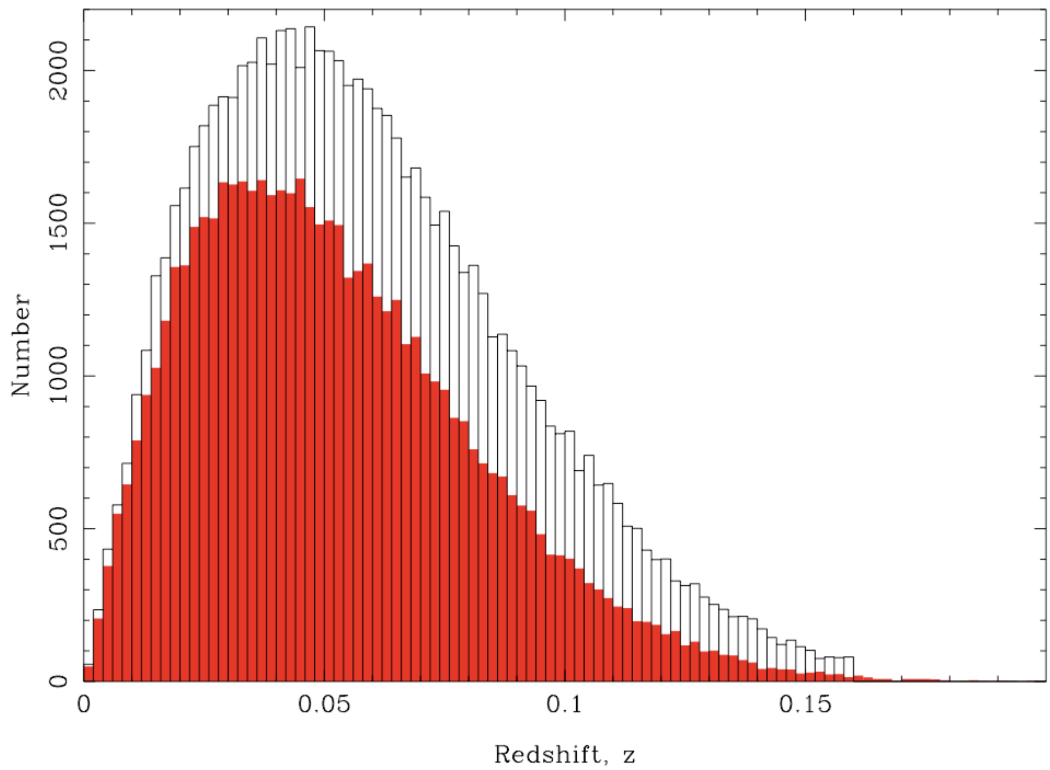

Figure 1: A simulated redshift distribution of galaxies detected in a 1-yr 2π survey with the FAST strawman design (upper histogram), overlayed on a simulated 1-yr 2π survey with the ASKAP strawman design (solid red histogram). A non-evolving HI mass function is assumed following Zwaan et al. (2005), and simulated galaxies are detected at the 5-σ level. The simulated FAST noise level is based on a gridding kernel similar to that used for HIPASS (Barnes et al. 2001).

The frequency response of the 19-beam FAST receiver is well-matched to the sensitivity of FAST in that the high-redshift cutoff at 0.16 is well above the mean galaxy redshift. Nevertheless, galaxies which have HI masses greater than 10^{10} $M_{\odot}$, and which are detectable with ASKAP, will be missing in a FAST survey above z=0.16. This population may be important in beginning to explore whether gas evolution is mild or extreme. On the other hand, the suggested 7-beam FAST receiver does not have as high a survey speed as a 19-beam receiver (Table 1), but its smaller physical size will theoretically allow a higher redshift limit. Figure 2 suggests that around 1000 new galaxies will be detected at z>0.16, with the actual number being very sensitive to changes in the high-mass end of the HI mass function.

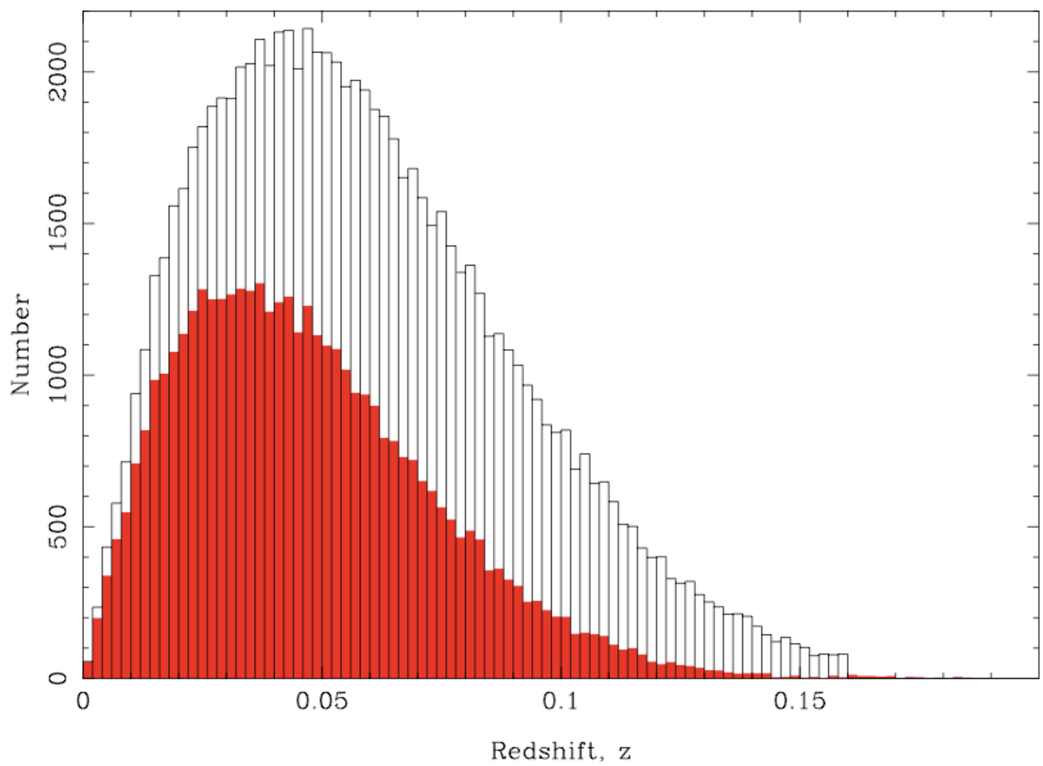

Figure 2: A simulated redshift distribution of galaxies detected in a 1-yr all-sky survey with FAST using similar assumptions to Fig.1. The upper histogram is the prediction for a 19-beam receiver operating above 1.23 GHz (z<0.16) and a single beam receiver otherwise; the lower (red) histogram assumes a 7-beam receiver at all frequencies.

3. The Deepest Surveys

Substantial differences in the survey speed of FAST relative to ASKAP occur at z>0.16 where the former reduces abruptly by a factor of 19. The inverse square dependence of the field-of-view on frequency allows some of the speed to be recovered at lower frequencies. However, Table 1 shows that, at 0.8 GHz (z=0.78), FAST remains 2.5 times slower than the strawman ASKAP design and more than an order of magnitude slower than the ASKAP expansion option. On the other hand, a 7-beam FAST receiver, if it were able to operate over the full frequency range, would recover much of the lost mapping speed.

To show the effect of receiver specifications on deep surveys, I compare the deepest HI surveys that FAST and ASKAP might be able to make. Both surveys are assumed to be for 1 yr and to extend to redshifts up to unity (I ignore the limitations on processed bandwidth which may be severe for ASKAP). In the case of FAST, I assume a survey area of 1000 arcmin^2, corresponding to about 35 beam areas at 0.8 GHz. Any less than that is difficult for a single dish because of bandpass calibration requirements. It's also the close to the spectroscopic self-confusion limit (10^3 galaxies per beam area per unit redshift) and beyond the cosmic variance limit. A greater survey area will detect more galaxies, but at correspondingly lower redshifts. In the case of ASKAP, the minimum survey area is the detector field-of-view of 30 deg^2.

The simulated redshift distribution for the strawman FAST and ASKAP deep surveys is shown in Figure 3. The greater survey area and the higher survey speed of ASKAP result in vastly more detections. However, at z>0.65, FAST is able to use its superior noise level to begin to detect more massive galaxies than the ASKAP deep survey.

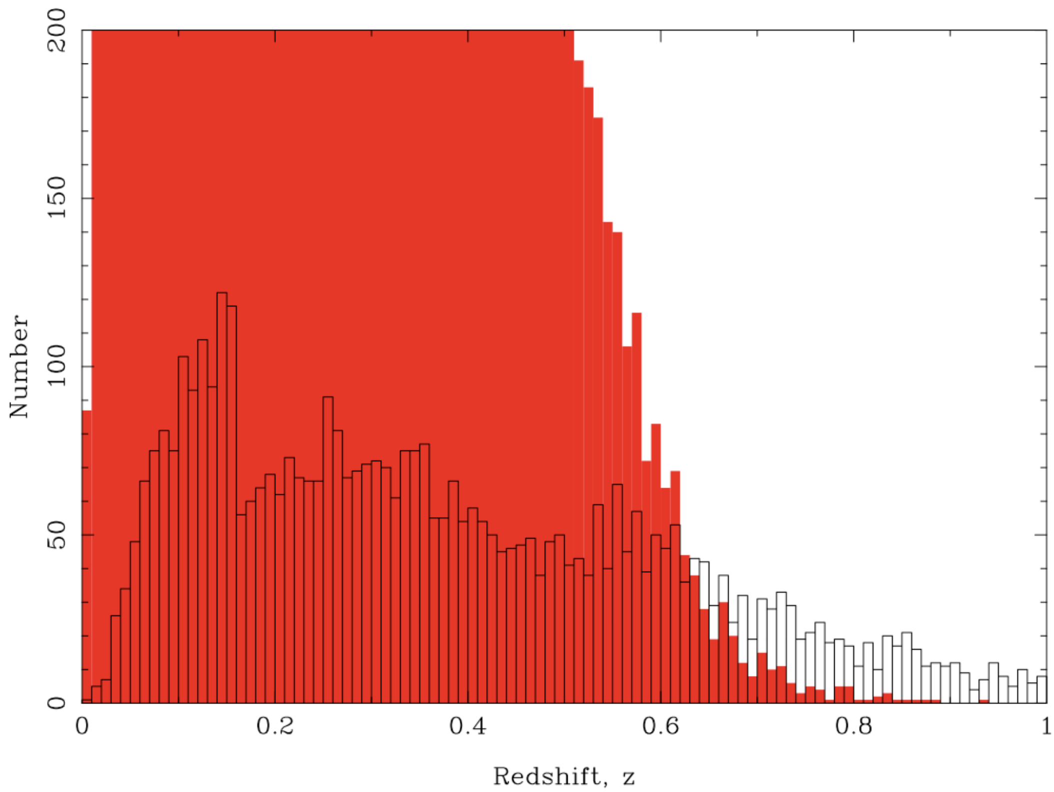

Figure 3: A simulated redshift distribution of galaxies detected in a 1-yr deep survey of 1000 arcmin^2 with the strawman FAST design (outline histogram), compared with a simulated 1-yr deep survey of a single 30 deg^2 pointing with the ASKAP strawman design (solid red histogram). A non-evolving HI mass function is assumed following Zwaan et al. (2005), and simulated galaxies are detected at the 5-σ level.

However, the gains to be made at z>0.65 with a 7-beam receiver are more impressive. Figure 4 shows a comparison of the simulated redshift distribution of the strawman FAST design and the wideband 7-beam option. At z<1, around 4500 galaxies can be detected with the strawman design, compared with 11,000 galaxies with the wideband option. The latter includes many 'normal' M_* galaxies at z=1.

This will allow precision estimates to be made of the cosmic gas density at redshifts double that obtainable with ASKAP.

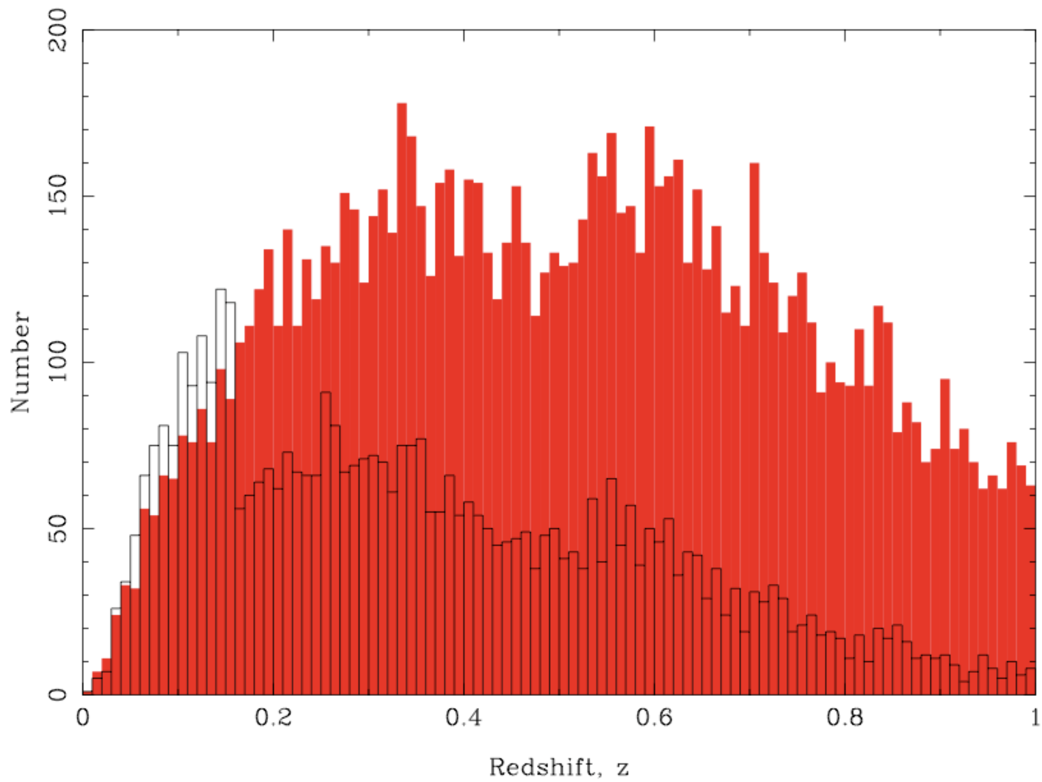

Figure 4: A simulated redshift distribution of galaxies detected in a 1-yr deep survey with FAST using similar assumptions to Fig.1. A small area of 0.3 deg^2 is simulated. The outlined histogram is the prediction for a 19-beam receiver operating above 1.23 GHz ($z<0.16$) and a single beam receiver otherwise; the upper (red) histogram assumes a 7-beam receiver at all frequencies.

4. Confusion

The low angular resolution of FAST compared with interferometers such as ASKAP is an advantage when it comes to efficiently detecting galaxies (more of the flux is confined to a single beam). However, it is a disadvantage when it comes to the identification of the optical/IR counterparts of objects, which is important for many science goals. For example, HIPASS (Meyer et al. 2004) was unable to unambiguously locate optical counterparts for 38% of its detections because of the low telescope resolution (Doyle et al. 2005). Although the angular resolution of FAST is better than Parkes by a factor of 5 or so, the distances of the galaxies detected in the shallow survey will be a similar factor greater than for HIPASS.

However, although it remains a challenging issue, it's important to note that confusion becomes less of an important issue when adequate optical redshift data are available. For the FAST shallow survey, SDSS provides optical data over a very complementary redshift range. For deep FAST surveys, various other optical surveys such as GAMA provide a possible source of optical redshifts. Moreover, forthcoming LAMOST surveys will provide even deeper redshift catalogues. Although these will probably be insufficient to resolve confusion in the deep

FAST survey considered above (which, as already noted, is close to being spectroscopically self-confused) they ought to be adequate for many other surveys.

For example, the average density of galaxies brighter than r=17.8 mag is ~0.3 per beam area for FAST (Strauss et al. 2002). Angular clustering raises the local density by a factor of 4 over the FAST beam at z=0.09 (Maller et al. 2005), giving rise to an angular confusion rate in excess of unity. However, with redshift information, the average number of M_* (and above) galaxies in a FAST beam in an interval Δz=0.001 will be around 0.01, which is 2 orders of magnitude better[2]. At z=0.42 (1 GHz), the number of M_* (and above) galaxies in the same redshift interval will be ~0.1, so identification will remain possible at the 90% confidence level. However, at z=0.78, the number of M_* (and above) galaxies in the same redshift interval will be 1.3. Galaxies detected at the deepest redshifts will be thoroughly confused.

At redshifts above ~0.1, photometric redshifts derived from multi-band photometry planned with surveys such LSST and Pan-Starrs (expected accuracy about Δz=0.05; Hildebrandt, Wolf & Benitez 2008) may also be very useful in cases where spectroscopic redshifts are unavailable.

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[2] There is assumed to be no evolution in the comoving HI mass function and no evolution in clustering strength