HI specs

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Some sensitivity calculations for SKA1 and SKA2 as well as expected dn/dz and bias from HI galaxies. Some of the results to appear in [1].

I. SENSITIVITY CALCULATIONS

A. Noise calculations

The noise associated to the flux measured by the interferometer is assumed Gaussian with a rms given approximately by

$$\sigma_S \approx \frac{2k_B T_{\rm sys}}{A_{\rm eff}\sqrt{\delta\nu\, t_p}}, \tag{1}$$

for an array with total effective collecting area $A_{\rm eff}$, frequency resolution $\delta\nu$ and observation time per pointing t_p (k_B is the Boltzmann constant). Telescope sensitivities are sometimes quoted in terms of the "System Equivalent Flux Density": SEFD $\equiv 2k_{\rm B}T_{\rm sys}/A_{\rm eff}$ or just "A over T": $A_{\rm eft}/T_{\rm sys}$. The effective collecting $A_{\rm eft}$ is usually 70% to 80% of the actual array total area depending of the efficiency of the system. Note that the expression above gives the flux sensitivity per resolution beam (not to confuse with the dish primary beam or telescope field of view). The equivalent brightness temperature uncertainty is

$$\sigma_T = \frac{\sigma_S c^2}{2k_B\nu^2(\delta\theta)^2}, \tag{2}$$

where $\delta\theta$ is the angular resolution of the interferometer. The total temperature is

$$T_{\rm sys} = T_{\rm inst} + T_{\rm sky} \tag{3}$$

with $T_{\rm sky} \approx 60\left(\frac{300\,{\rm MHz}}{\nu}\right)^{2.55}$ K and $T_{\rm inst}$ the instrument temperature which is usually higher than the sky temperature above 300 MHz. For typical instrument specifications, the single-dish noise rms can be written as:

$$\sigma_S = 368\,\mu{\rm Jy}\left(\frac{T_{\rm sys}}{20\,{\rm K}}\right)\times \left(\frac{25,000\,{\rm m}^2}{A_e}\right)\left(\frac{0.01{\rm MHz}}{\delta\nu}\right)^{1/2}\left(\frac{1{\rm h}}{t_{\rm p}}\right)^{1/2}. \tag{4}$$

For a given survey area, $S_{\rm area}$ we will need $S_{\rm area}/(\theta_{\rm B})^2$ pointings where $(\theta_{\rm B})^2$ is the telescope field of view with the full width at half maximum of the beam, given by (in radians)

$$\theta_{\rm B} \approx 1.22\lambda/\sqrt{(A_{\rm dish})}, \tag{5}$$

where $A_{\rm dish}$ is the effective area of each dish. The time per pointing t_p is then related to the total integration time $t_{\rm tot}$ through

$$t_p = t_{\rm tot}\frac{(\theta_{\rm B})^2}{S_{\rm area}}. \tag{6}$$

This will increase the time per pointing at the lowest frequencies. Note that in the table below, following what is in the SKA baseline document we use instead

$$\theta_{\rm B} \approx \frac{\pi}{4}(\frac{66\lambda}{D})^2\ [{\rm deg}^2]. \tag{7}$$

Also, the computed PAF beams are assumed constant across the band instead of going as λ^2 as above so that the time per pointing is also fixed.

B. Telescope specs

Table I summarises the specifications for each telescope.

C. Survey specs

Table II summarises the specifications for each survey.

II. HI GALAXY SURVEY

To calculate the HI galaxy number density and bias as a function of flux rms, we used the SAX-sky simulation[1]. For the detection of a galaxy, we required that at least two points on the HI line are made, that is, the width of the line has to be larger than $2\times$ the assumed frequency resolution of the survey. The idea is to get some information on the typical line double peak expected from HI

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[1] http://s-cubed.physics.ox.ac.uk/s3_sax

Telescope	Band [MHz]	z	$T_{\rm inst}$ [K]	$N_{\rm dish}$	$D_{\rm dish}$ [m]	$A_{\rm eff}$ [m^2]	beam [deg^2] [1]	SEFD [Jy]	Flux rms [μJy] [2]
SKA1 - Mid	350 - 1050	0.35 - 3.06	28	190	15	21,824	2.8	3.54	590
SKA1 - Mid	950 - 1760	(0) - 0.50	20	190	15	26,189	0.75	2.1	350
MeerKAT	580 - 1015	0.40 - 1.45	29	64	13.5	6,413	2.63	8.61	1435
MeerKAT	900 - 1670	(0) - 0.58	20	64	13.5	5,955	1.0	9.27	1546
Mid+MK	580 - 1015	0.40 - 1.45	28.5	254	–	28,237	2.15	2.79	464
Mid+MK	950 - 1670	(0) - 0.50	20	254	–	32,144	0.8	1.72	286
SKA1-Sur	350 - 900[3]	0.58 - 3.06	50	60	15.0	8,482	61[4]	16.28	2713
SKA1-Sur	650 - 1670[3]	(0) - 1.19	30	60	15.0	8,482	18[4]	9.77	1628
ASKAP	700 - 1800[5]	(0) - 1.03	50[9]	36	12.0	3,257	30[4]	42.4	7065
Sur+ASKAP	700 - 1670[5]	(0) - 1.03	38.7	96	–	11,740	18[4]	9.1	1518
SKA2	500 - 1200[6]	0.18 - 1.84	20	250	50[7]	400,000	100[8]	0.14	23

TABLE I. Telescope configurations.
[1] This is the primary beam (FoV) calculated at the center of the band. It changes as λ^2. For the combined telescopes, the smallest beam of the two telescopes is used.
[2] Flux rms for a frequency interval of 0.01 MHz and 1 hour integration using eq. 4.
[3] Only 500 MHz instantaneous bandwidth.
[4] PAF beams assumed constant across the band.
[5] Only 300 MHz instantaneous bandwidth.
[6] Band only indicative - can be changed.
[7] These should be stations (dense aperture arrays).
[8] Assuming multi-beaming to obtain large field of view.
[9] Although the SKA baseline document quotes 30 K, most specs for ASKAP so far shows 50 K as the target system temperature and we opted to use this last value.

Telescope	Band [MHz]	beam [deg^2]	Survey area [deg^2]	t_p [hours]	Flux rms [μJy]
SKA1 - Mid	350 - 1050	1.38[1]	5,000	2.76[1]	355[2]
SKA1 - Mid	950 - 1760	1.38[1]	5,000	2.76[1]	211[2]
MeerKAT	580 - 1015	1.67[1]	5,000	3.34[1]	785[2]
MeerKAT	900 - 1670	1.67[1]	5,000	3.34[1]	846[2]
Mid+MK	580 - 1015	1.38[1]	5,000	2.76[1]	279[2]
Mid+MK	950 - 1670	1.38[1]	5,000	2.76[1]	172[2]
SKA1-Sur[3]	350 - 900	61	5,000	122	246
SKA1-Sur[3]	650 - 1670	18	5,000	36	271
ASKAP[3]	700 - 1800	30	5,000	60	912
Sur+ASKAP[3]	700 - 1670	18	5,000	36	253
SKA2[3]	500 - 1200	30	30,000	10	7.27

TABLE II. Survey specifications. We assume a total observation time of 10,000 hours. The flux rms is calculated for a frequency interval of 0.01 MHz. Values were calculated at the target frequency of 1.0 GHz, except for SKA1-Sur band 1 which has an upper limit of 900 MHz.
[1] The beam and time per pointing (t_p) are assumed to change as $(\frac{1.0\,{\rm GHz}}{\nu})^2$ across the band.
[2] The flux rms is assumed to change as $\frac{\nu}{1.0\,{\rm GHz}}$ across the band.
[3] The beam, time per pointing and flux rms are assumed constant across the band.

galaxies due to their rotation. This in principle will remove any galaxy that is seen "face on" as it will show just a narrow peak. More evolved source detection methods can (and should) be explored, to avoid spurious detections due to RFI, but we will keep this simple approach for now. A signal to noise of 10 is then required for the detection of a galaxy.

Using the SAX database, we used the following variables and prescription to detect HI galaxies:

- "zapparent" - Apparent redshift (including Doppler correction).
- Set experiment spectral resolution to $dV = 2.1(1+$ zapparent) (in Km/s). This corresponds to a frequency resolution of 0.01 MHz which is what has been assumed for the sensitivity calculations.
- "hiwidthpeak" [Km/s] - Line width between the two horns of the HI-line profile (already corrected for the galaxy inclination).

- Take only galaxies where hiwidthpeak/2 $> dV$
- "hiintflux" [Jy Km/s] - Velocity-integrated line flux of the HI-line.
- For each galaxy get flux = hiintflux/hiwidthpeak.
- Take only galaxies where flux $> 10 \times$ (flux rms)$/\sqrt{(\text{hiwidthpeak}/dV)}$.

In order to be as general as possible we didn't try to match completely the flux rms used in the query to the above survey specs. Instead we are giving results for several values so that a simple interpolation can be used if we decide to change the survey specs. In particular, if we decide to use a 5σ cut instead of a 10σ, it is just a question of looking for the numbers corresponding to the flux rms that is half the survey value.

To obtain the bias, the "detected" galaxies were put in a box, for which the power spectrum of the number counts was calculated. The bias squared was then taken as the ratio of that power spectrum to the dark matter one at $k = 0.2$ h/Mpc. The SAX-sky simulation consists in a mock observing cone with galaxies and their properties. This simulation was built to add HI and CO properties to the galaxies obtained by [2] using the millennium simulation [3]. The millennium simulation has a box size of 500 h^{-1} Mpc and its galaxies are available at 64 fixed time steps from redshifts 127 to 0. In order to properly emulate the light cone, the SAX-sky simulation used only part of each box of the millennium simulation as is described in [4]. Therefore, the boxes at fixed redshifts with HI properties which can be obtained from the SAX-sky simulation are considerable smaller than 500 h^{-1} Mpc in the line of sight direction.

To perform this study we used boxes with different sizes from $L_\parallel = 58h^{-1}$ Mpc and $L_\perp = 100h^{-1}$ Mpc for redshift 0.06 to $L_\parallel = 162h^{-1}$ Mpc and $L_\perp = 398h^{-1}$ Mpc for redshift 2.07. This puts a problem on the bias extraction since we cannot efficiently use modes below $k \sim 0.1$ h/Mpc. For high flux rms, the number of galaxies is low and the shot noise dominates up to very small ks. The conclusion is that for high flux/redshift values the results should be taken as only an indication, in particular for bias above $\sim 20\mu$Jy flux rms. As an example we show in Figure II the dimensionless HI galaxy power spectrum at $z = 1$ for different sensitivities. Also note that the Millenium simulation only has galaxies with masses $\gtrsim 2\times10^{10}$ Msun and therefore the bias and number density for rms=1 might be affected by the lack of smaller galaxies. However this should not affect the statistics for higher rms values. The cosmological analysis should compare results for different fiducial values and fully marginalise over the bias and number counts.

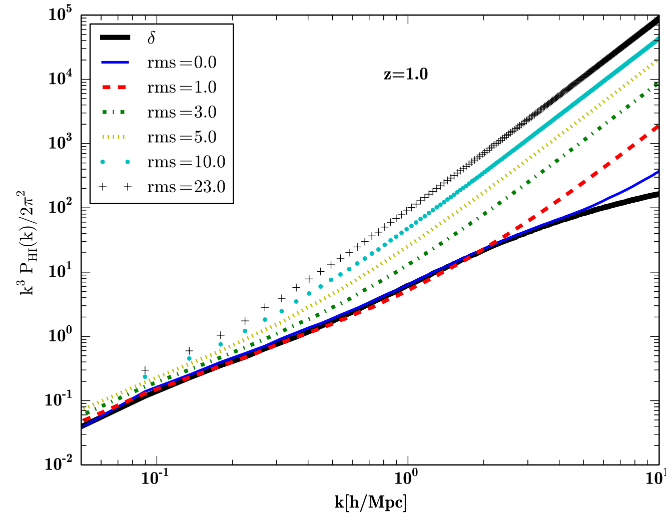

FIG. 1. The dimensionless HI galaxy power spectrum for different sensitivities (the actual galaxy flux cut will be higher than this as described). Black solid line shows the dark matter power spectrum from CAMB. The straight lines at high k indicate shot noise.

III. ATTACHED FILES

- **HIdndz.txt**: contains the $\frac{dn}{dz}$ [deg^{-2}] for different cuts using the process described above. Note that each column indicates the corresponding flux rms not the flux cut.
- **HIbias_squared.txt**: contains the corresponding bias squared.

IV. FITTED dn/dz AND $bias$

In order to fit the values for dn/dz we used the function:

$$dn/dz = 10^{c_1} z^{c_2} \exp\left(-c_3 z\right), \tag{8}$$

where c_i are free parameters. Fig. 2 top panel shows the fitted curves and the data points. The fitted parameters are given in Table III.

For the galaxy bias data points, they are shown in Fig. 2 bottom panel for different S_{rms} sensitivities. We use an exponential function to fit the galaxy bias $b(z)$ to the simulated data:

$$b(z) = c_4 \exp(c_5 z). \tag{9}$$

Values of the fitted parameters for each r.m.s sensitivity are given in Table IV.

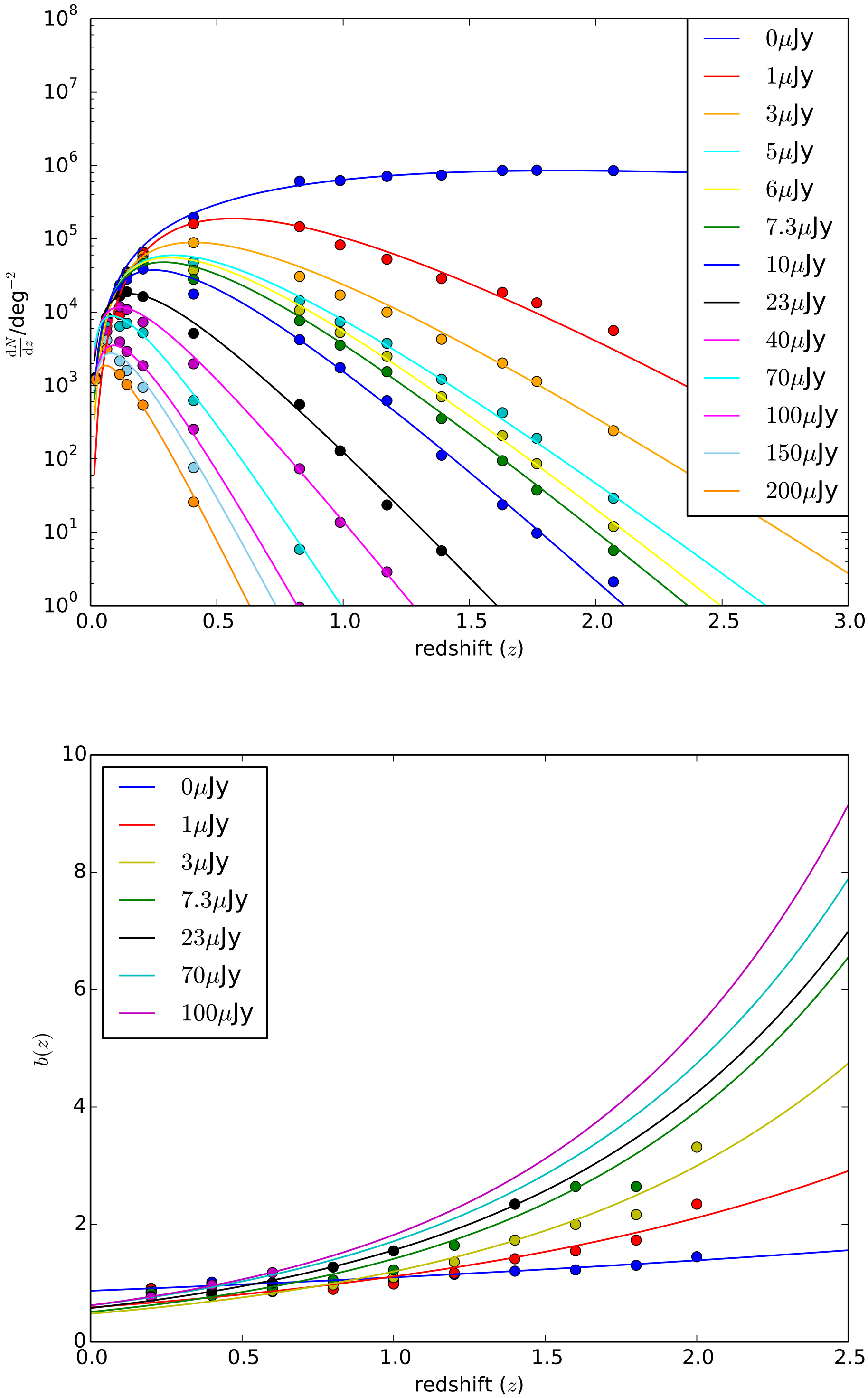

FIG. 2. Upper panel: Dependence of the HI galaxy redshift distribution dn/dz (units: $\deg^{-2}$). Note that the numbers are for different flux rms which will correspond to a given galaxy flux cut according to the procedure described in the text. Curves are the fits according to Eq. (8) and dots are from the S^3-SAX simulation. Lower Panel: HI galaxy bias for different $S_{\rm rms}$. Note that above 70 μJy values for high redshifts are purely extrapolations. However, this has little impact as at high z shot noise will dominate for these sensitivities.

TABLE III. Values of the fitted parameters of Eq. (8), for different $S_{\rm rms}$.

$S_{\rm rms}$ [μJy]	c_1	c_2	c_3
0	6.23	1.82	0.98
1	7.33	3.02	5.34
3	6.91	2.38	5.84
5	6.77	2.17	6.63
6	6.84	2.23	7.13
7.3	6.76	2.14	7.36
10	6.64	2.01	7.95
23	6.02	1.43	9.03
40	5.74	1.22	10.58
70	5.62	1.11	13.03
100	5.63	1.41	15.49
150	5.48	1.33	16.62
200	5.00	1.04	17.52

TABLE IV. Values of the fitted parameters of Eq. (9), for different $S_{\rm rms}$. For higher flux cuts we suggest to take $b(z)$=1 as we can only use galaxies below $z \sim 0.5$.

$S_{\rm rms}$ [μJy]	c_4	c_5
0	0.8695	0.2338
1	0.5863	0.6410
3	0.4780	0.9181
5	0.5884	0.8076
6	0.5908	0.8455
7.3	0.5088	1.0222
10	0.4489	1.2069
23	0.5751	0.9993
40	0.5125	1.1842
70	0.6193	1.0179
100	0.6212	1.0759

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