HI Surveys and the xNTD Antenna Configuration

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Abstract

Sizes are estimated for galaxies expected to be detected in nominal xNTD all-sky and deep surveys. In order to maximise both the ability to detect large numbers of galaxies, and to permit good identification accuracy at other wavebands, a resolution of around 30 arcsec is desirable. Smaller beams reduce detection efficiency, whereas larger beams result in too much confusion and positional inaccuracy. The synthesised beam should have relatively low sidelobes, as the HI surveys may not have the signal-to-noise ratio (or computing capacity) for quality deconvolution. A Gaussian beam is preferable as this approximately matches the radial profile of many galaxies in HI. To maximise signal-to-noise ratio and the cost-effectiveness of the xNTD HI surveys, the above beam needs to be synthesised from the *naturally-weighted* data.

1. Introduction

The xNTD is a widefield instrument designed to conduct spectral-line and radio continuum surveys of the sky. Although the proposed total collecting area and system temperatures are not spectacular (3500 m^2 and 50 K, respectively; Johnston 2006), the small antenna size (12 to 15 m) and the multi-element array at the focal plane create a massive field of view (~40 deg^2 at 1 GHz) ideal for long integrations over large areas of sky.

One of the headline goals of the xNTD is a large-scale survey of galaxies in HI. There is a good case for surveys of different depth, covering different areas of sky. In this memo, I focus on two surveys, which represent the extreme of what is possible with xNTD, will take the most observing time, and should therefore help further define the xNTD antenna configurations. The surveys are:

1. All-sky HI survey: broadly speaking, this is a survey of the sky visible to xNTD. The northern limit will be defined by the northern horizon unless new northern hemisphere arrays (e.g. WSRT/Apertif, Allen Telescope Array) will be doing similar science on a similar timescale. The southern survey may be shared with the South African KAT project. A year of integration time should detect around 500,000 galaxies at redshifts up to 0.2.

2. Deep HI survey: being an interferometer, it is expected that the noise from an xNTD ‘pencil-beam’ will continue to decrease with longer integrations. This

survey will focus on a single patch of sky and, again, involve integration times of a few hundred days. Johnston (2006) gives an example where 70,000 galaxies are detected over 120 deg^2 in 100 days out to a limiting redshift of ~0.6.

2. General Remarks

The object of the HI surveys is to detect as many galaxies as possible, whilst gaining the maximum amount of information about their properties. As far as spatial resolution is concerned, the appropriate balance is probably one in which the bulk of the higher-redshift and fainter objects are not resolved, but that some resolution is available for sub-samples of closer objects. HIPASS was able to detect as many as ~5000 galaxies (Meyer et al. 2004, Wong et al. 2006) as there was little dilution of flux in the beam of the Parkes telescope. For single dishes, too much resolution kills sensitivity by spreading flux over several beams, decreasing signal-to-noise ratio by the number of beams covering the object, or the square root of that number if a matched filter can used. Similar considerations apply to interferometers, although the exact loss of sensitivity critically depends on the distribution of baseline lengths. HIPASS did however suffer by having a substantial number of objects where the positional accuracy was insufficient resolution for accurate galaxy identification. This argues for *a spatial resolution which is coarser than, but not much coarser than, the object size for the faintest and most numerous type of object*, i.e. those near the limit of the surveys.

Under such circumstances, it expected that the HI surveys will be limited by thermal noise rather than confusion, or source crowding. This is because the different sky frequencies of the redshifted HI lines readily allow the xNTD backend to spectrally resolve any galaxies even if they are not are not spatially resolved. In this case, it is expected that most galaxy detections will be at flux densities which are close to the survey limit. For any galaxy survey, 65% of the detections will lie within a factor of 2 of the limiting survey depth, independent of the HI mass function, as long as it is homogeneous (appropriate for the all-sky survey, but possibly not for the deep survey). Because deconvolution techniques are unstable in the presence of noise (Starck, Pantin & Murtagh 2002), and because we want to avoid the situation where half the survey images are deconvolved and the other half not, I suggest that deconvolution be avoided. Therefore, a requirement for the HI surveys is that *the synthesised beam should be relatively free of sidelobes*. This has the added advantage of hugely decreasing computational overheads. The ideal shape for the synthesised beam is a Gaussian, as this matches the spatial profile of many galaxies.

Locating a few antennas in a dense core, or in outlying locations, degrades the quality of the synthesised beam. Such arrays will produce high sidelobes, reduce the reliability of the survey and compromise the quality of the flux densities. Baselines to such antennas would be eliminated or down-weighted in the HI surveys. Although such configurations may be attractive for other science, it makes the HI science more costly in observing time to achieve a given sensitivity. The corollary is that *HI surveys would like to achieve their ideal Gaussian beam using 'natural weighting' where data from all interferometer baselines is given equal weight, regardless of baseline length or position in the uv-plane.*

3. Angular Resolution

Neutral hydrogen in galaxies tends to have a limited range of column density. Column densities above the peak column density of 1.1×10^{22} atoms cm^{-2} observed in the SMC (Stanimirovic et al 1999) are absent – such gas tends to readily form into molecular phase. Similarly, it is rare to find column densities below 10^{19} cm^{-2} (Staveley-Smith et al. 1998), probably because of photoionisation (Maloney 1993). Samples of normal galaxies (e.g. Broeils & van Woerden 1994) tend to have mean column densities very close to 3.8×10^{20} cm^{-2}. A result of this narrow column density range is a well-defined correlation between the HI masses and the HI extent of galaxies.

Meyer et al. (2004) parameterise the flux-size[1] relationship as P (Jy km s^{-1}) = 1.2 ϑ^2 ($arcmin^2$). At low redshifts, this relationship is distance-independent. For the redshift range of interest here, it is more appropriate to: (a) take into account the effect of cosmological dimming[2]; and (b) use a modified flux definition P that varies as the inverse square of luminosity-distance for a standard candle. A revised parameterisation is therefore is P (Jy km s^{-1}) = 1.2 ϑ^2 ($arcmin^2$) $(1+z)^{-3}$ or P (Jy kHz) = 5.7 ϑ^2 ($arcmin^2$) $(1+z)^{-4}$.

Frequency resolution	100 kHz		1 MHz	
S/N ratio	5-σ	10-σ	5-σ	10-σ
All Sky Survey				
Flux *P* (Jy kHz)	0.22	0.45	0.71	1.41
Size, z=0	12 arcsec	17 arcsec	21 arcsec	30 arcsec
Size, z=0.1	15 arcsec	21 arcsec	25 arcsec	36 arcsec
Size, z=0.2	17 arcsec	24 arcsec	30 arcsec	43 arcsec
Deep Survey				
Flux *P* (Jy kHz)	0.019	0.038	0.06	0.12
Size, z=0	3 arcsec	5 arcsec	6 arcsec	9 arcsec
Size, z=0.2	5 arcsec	7 arcsec	9 arcsec	13 arcsec
Size, z=0.4	7 arcsec	10 arcsec	12 arcsec	17 arcsec
Size, z=0.6	9 arcsec	13 arcsec	16 arcsec	22 arcsec

Table 1: Estimated flux limits and mean galaxy diameters for the xNTD all-sky (1 yr, 20626 deg^2) and deep HI (100 days, 40 deg^2) surveys for different frequency resolutions and signal-to-noise ratios. A frequency interval of 100 kHz corresponds to a rest-frame velocity interval of $21(1+z)$ km s^{-1}, corresponding to an extremely face-on galaxy or a dwarf; a frequency interval of 1 MHz corresponds to a rest-frame velocity interval of $211(1+z)$ km s^{-1}, more typical of galaxies detected in HI surveys.

[1] HI size is defined as the diameter to a HI surface density of 1 $M_\odot$ pc^{-2}, corresponding to a column density of 1.26×10^{20} cm^{-2}.
[2] The Tolman (1930) effect. Over the redshift range of interest, gaseous evolution may be more important.

For xNTD sensitivity, I use the values of Johnston & Gray (2006) where a 1-hr integration on a field results in an rms of 8.2 mJy over a frequency interval of 5 kHz. With scaling appropriate to the all-sky and deep HI surveys, I therefore list the expected HI size of galaxies at the 5-σ and the 10-σ flux limits of the HI surveys and at different redshifts in Table 1.

At the 5-σ flux limit of the surveys, I therefore expect galaxies to have sizes of 21 arcsec-30 arcsec in the all-sky survey and 6 arcsec-16 arcsec in the deep survey, depending on redshift. Furthermore, most of the galaxies in the surveys will be smaller than 30 arcsec-43 arcsec and 9 arcsec-22 arcsec for the all-sky and deep surveys, respectively. A reasonable *lower limit* to the angular resolution of the HI surveys is therefore 30 arcsec - any better (less) than 30 arcsec, and flux will be lost for a significant number of survey objects. However, resolutions significantly coarser than 30 arcsec will lead to identification problems, and will reduce the ability of xNTD to undertake imaging studies of the samples of larger, more nearby objects.

4. Identification Accuracy

For an unresolved galaxy, the measured positional accuracy is proportional to synthesised beamwidth and approximately inversely proportional to signal-to-noise ratio. So, although self-confusion may not be an issue with xNTD HI surveys, the ability to locate the counterpart to an HI detection at optical, infrared or other wavebands is an important issue. HIPASS, for example, suffered from insufficient positional accuracy to unambiguously find the optical counterparts for 38% of its detections (Doyle et al. 2005). The HIPASS beam (15.5 arcmin) at the depth of HIPASS (z=0.01) corresponds to a linear size[3] of 190 kpc. At the nominal mean depths of the xNTD all-sky (z=0.1) and deep surveys (z=0.2), this corresponds to a beamwidth of 90 arcsec and 42 arcsec, respectively. These are indicative *upper limits* for the xNTD beamwidth.

A more useful estimate is probably obtained by considering the integrated density of galaxies brighter than red magnitude r=17.8 in SDSS-I (Strauss et al. 2002), which is around 90 deg^{-2}. Such galaxies, which have a mean redshift of 0.1, generally only have redshifts in the π steradians near the NGP surveyed by SDSS and 2000 deg^{-2} near the SGP surveyed by the 2dFGRS (Colless et al. 2001).

Therefore, if we want the probability of a chance coincidence with a randomly located xNTD detection to be less than 1%, a simple Poisson estimate indicates that the 2D positional accuracy needs to be 21 arcsec, or better (~10 arcsec at z=0.2). Clustering raises this probability and increases the positional accuracy required. The length scale over which we find that the probability of finding an HI-selected galaxy is double that of the Poisson probability is 4.7 Mpc (Meyer et al. 2006). Where the redshifts of the matching population are not known, knowledge of the angular correlation function is required. The 2MASS survey, which has a similar median redshift of 0.07, has a galaxy-galaxy angular correlation function of the form $W(\theta)=0.1\theta(\mathrm{deg})^{-0.79}$ (Maller et al. 2005). Using this to approximate the xNTD-2MASS cross-correlation function, the

[3] H_o=73 km s^{-1} Mpc^{-1}, Ω_m=0.3, Ω_Λ=0.7.

probability of angular coincidence, which is $1+W(\theta)$ times the Poisson probability, therefore becomes 6.8% for a positional accuracy of 21 arcsec.

In practice, the 30 arcsec beam discussed in Section 4 will give a positional accuracy of around 6 arcsec, or better, at the survey limit. At this angular separation, the total coincidence probability will be acceptably small at 1.3% for 2MASS depths.

Summary

Considerations of intrinsic galaxy size in the xNTD all-sky and deep HI surveys suggest that a beamsize of around 30 arcsec may be a suitable target in that it balances the two competing desires to: (a) allow a significant number of galaxies to be detected without loss of a large amount of flux through over-resolving; (b) allow the measurement of positions sufficiently accurate to permit identification at other wavebands. A suitable reference redshift is 0.2, which corresponds to a sky frequency of 1184 MHz. At this frequency, 30 arcsec corresponds to a maximum array baseline of approximately 2 km, depending on the exact antenna configuration.

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