Science with the Extended New Technology Demonstrator

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1 Introduction

The New Technology Demonstrator (NTD) is an Australian concept in the development of the Square Kilometer Array (SKA). The key concept behind the NTD is to demonstrate wide field-of-view operations on a ∼15 m parabolic dish using a large (∼100 element) focal plane array. The NTD is fully funded through mid 2007 via the Major New Research Facility (MNRF) program initiated by the Federal Government.

The xNTD is the Extended version of the NTD and is designed to be a front-line scientific instrument in its own right. It builds upon the deliverables from the NTD and other MNRF projects and benefits from international collaborations with other interested parties. The xNTD will consist of at least 20 dishes, each of about 15 m diameter and equipped with a focal plane array capable of producing a field-of-view of 40 square degrees at 1 GHz. It will be located in Mileura, Western Australia at the proposed Australian site for the SKA. Initial funding for research and development of the xNTD has come from the CSIRO. Additional funds have been provided by the Government of Western Australia and are actively being sought from the Federal Government's National Collaborative Research Infrastructure Strategy (NCRIS) which has recognised astronomy as a priority area.

The xNTD is part of the strategic pathway towards the SKA as outlined in the Australian SKA Consortium Committee's "SKA: A Road Map for Australia" document. The xNTD is seen as '...a significant scientific facility, maintaining Australia's leading role within the SKA partnership and addressing key outstanding computational/calibration risk areas ...'. SKA programs were given the highest priority for Australian radio astronomy in the 2006-2015 Decadal Plan for Astronomy. Although the collecting area of the xNTD is less than 1% that of the SKA, the technological solutions it proposes are designed to ensure a modular upgrade path towards the 10% SKA Phase I and the full SKA, provided the technical challenges can be met.

The xNTD will demonstrate 'smart feed' technology for the SKA, and should also demonstrate the feasibility of the science projects envisaged for the full SKA. In particular, five key science projects (KSPs) have been adopted by the International SKA Steering Committee. These are

- The cradle of life (Lazio et al. 2004)
- Strong field tests of gravity using pulsars and black holes (Kramer et al. 2004)

- The origin and evolution of cosmic magnetism (Gaensler et al. 2004)
- Galaxy evolution, cosmology and dark energy (Rawlings et al. 2004)
- Probing the dark ages (Carilli et al. 2004)

The xNTD system parameters, in particular the frequency range, are aimed squarely at attacking the middle three of these KSPs. Several other experiments, co-located at the Mileura site, will target the 'Dark Ages' KSP which requires observing frequencies below about 200 MHz.

The headline goals for the xNTD are

- The detection of 500,000 galaxies in H I emission across the southern sky out to a redshift of 0.2 to understand galaxy formation and gas evolution.
- The detection of 10^7 continuum sources, 5×10^5 polarized sources and measurements of 60,000 rotation measures across the sky enabling cosmological tests and the evolution of cosmic magnetism.
- The characterization of the radio transient sky through detection and monitoring of transient sources such as gamma ray bursts, radio supernovae and intra-day variables.
- The discovery of up to 1000 radio pulsars.

2 System Parameters and overview

The parameters for the xNTD telescope are given in Table 1. These parameters should be considered as preliminary only; they are likely to undergo modifications as the technical specifications, cost and funding streams become better known.

I have derived elsewhere the survey speeds for an interferometer like the xNTD (Johnston & Gray 2006). To recap, the number of square degrees per second that can be surveyed to a given sensitivity limit, σ_s is

$$SS_s = F\ B\ n_p \left(\frac{A\ N\ \epsilon_a\ \epsilon_c\ \sigma_s}{2\ k\ T}\right)^2 \tag{1}$$

where F is the field of view in square degrees and all other parameters have their SI units. B is the bandwidth, n_p the number of polarizations, A is the collecting area of a single element, N is the number of elements and ϵ_a and ϵ_c represent dish and correlator efficiencies. The system temperature is T with k being the Boltzmann constant. The surface brightness temperature survey speed is given by

$$SS_t = F\ B\ n_p \left(\frac{\epsilon_c\ \sigma_t}{T}\right)^2\ f^2\ \epsilon_s^{-2} \tag{2}$$

Table 1: Possible system parameters for the xNTD

Parameter	Value	
Number of Dishes	20	
Dish Diameter	15 m	
Total collecting area	3534 m^2	
Aperture Efficiency	0.8	
System Temperature	50 K	
Number of beams	30	
Field-of-view at 1 GHz	40 deg^2	
Frequency range	$800 - 1700$ MHz	
Instantaneous Bandwidth	300 MHz	
Maximum number of channels	16000	
Maximum baseline	3000 m	
Continuum survey speed	2850 deg^2/hr	256 MHz, 0.3 mJy rms
Line survey speed	124 deg^2/hr	20 kHz, 10 mJy rms
Surface brightness survey speed	31 deg^2/hr	5 kHz, 1 K rms, 1’ resolution

where now σ_t denotes the sensitivity limit in K and f relates to the filling factor of the array via

$$f = \frac{A \ \epsilon_a \ N \ \Omega \ \epsilon_s}{\lambda^2} \tag{3}$$

Here, ϵ_s is a ‘synthesised aperture efficiency’ which is related to the weighting of the visibilities and is always ≤ 1.

There is interplay between these parameters when trying to maximise the survey speed for a given expenditure. For the science that will be considered here, the value of SS_s and SS_t are the critical parameters. We will therefore assume that the survey speeds listed in the table can be met by a suitable choice of A, N, F and T. One should also not neglect the total bandwidth available for a spectral line survey. If the total bandwidth is insufficient to cover the required bandwidth of a given survey, the survey speed suffers as a result of having to repeat the same sky with a different frequency setting.

The large field-of-view (FoV) makes the xNTD primarily a survey telescope. Although it has a slightly larger collecting area than the Parkes 64-m dish, its uncooled receivers reduces its raw, instantaneous sensitivity. As an interferometer the xNTD provides low frequency imaging not otherwise available at the Australia Telescope Compact Array (ATCA). Even for single pointings, it also exceeds the ATCA sensitivity at 1400 MHz and may have improved resolution if it also extends beyond 6 km baselines. In terms of survey speed however, it gains by large factors for both line, continuum and surface brightness sensitivity compared to existing facilities. The final three rows of Table 1 give survey speeds given the system parameters and the assumptions listed in column 3. Table 2 provides a comparison between the xNTD and other existing and proposed facilities.

Table 2: A comparison of the xNTD parameters with other instruments

Param	xNTD	VLA	ATCA	GMRT	PKS-MB	Arec-MB	ATA	CLAR
D	15	25	22	45	64	300	6.1	300
ϵ_a	0.8	0.51	0.8	0.4	0.8	0.8	0.8	0.7
N	20	27	5	30/20	1	1	350	1
M	50	1	1	1	13	7	1	166
T	50	33	35	70	22	35	50	50
ϵ_c	1.0	0.79	0.79	0.79	0.79	0.79	1.0	1.0
λ	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
FoV	41.0	0.29	0.38	0.09	0.58	0.014	5.0	0.3
continuum survey speed								
B (MHz)	256	64		256			256	256
σ_s (mJy)	0.3	0.3		0.3			0.3	0.3
SS	2850	42		92			2900	6400
line survey speed								
B (MHz)	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
σ_s (mJy)	10	10	10	10	10	10	10	10
SS	124	7.4	0.6	1.8	4.8	22	126	280
surface brightness survey speed								
B (MHz)	0.005	0.005	0.005	0.005			0.005	0.005
σ_t	1	1	1	1			1	0.1
θ	1	1	1	1			1	2.5
SS	31	1.9	0.1	0.46			32	44
raw sensitivity								
B (MHz)	1	1	1	1	1	1	1	1
σ_s (mJy)	1	1	1	1	1	1	1	1
t	1200	140	3100	80	440	2	140	4

The xNTD be will be located at one of the most radio quiet sites on Earth, in Mileura, Western Australia. Mileura is the Australian candidate site to host the SKA and will form the central element of a ‘Radio Astronomy Park’ in a protected Radio Quiet Zone. The choice of site ensures that the xNTD will be largely free of the harmful effects of radio interference currently plaguing the current generation of telescopes, especially at frequencies around 1 GHz and below. Being able to obtain a high continuous bandwidth at low frequencies is critical to much of the science described below. The southern latitude of the xNTD implies that the Galactic Centre will transit overhead and the Magellanic Clouds will be prominent objects of study.

There are several issues as regards the configuration and maximum baseline length for the xNTD. The detection of H I from galaxies requires a resolution no less than 15 arcsec (baselines less than 3 km). Galactic H I requires good surface brightness sensitivity, and, given the collecting area the optimum baseline length is around 200 m yielding a 3 arcmin beam. The computational demands of pulsar science also drive the configuration to short baselines. Finally, the all-sky continuum survey ideally requires long baselines to avoid confusion but not too long that sources get resolved. The NVSS and SUMMS both have a 45 arcsec beam at their respective frequencies (see the arguments in Condon et al. 1998) but there is a clear case for higher resolution. In particular, matching radio detections with objects at other wavebands ideally requires positional accuracy near 1 arcsec which would imply baselines of at least $\sim$3 km. Simulation studies will be performed to determine the best configuration for the science requirements.

A further important application of the xNTD is for Very Long Baseline Interferometry (VLBI), especially because of its location in Western Australia. The xNTD then provides significant collecting area on east-west baselines of $\sim$3000 km and enables the gap in coverage between east coast Australia and South Africa to be closed.

There is strong complementarity between large scale radio surveys and surveys at other wavelengths. A number of spectroscopic and continuum surveys are underway or in planning in the infra-red, optical and UV wavelengths. X-ray and γ-ray satellites have or will survey the entire sky to good sensitivity. A high resolution continuum survey, and a large-scale, deep spectroscopic survey in the radio therefore provides vital information at long wavelengths and are significant pieces of a giant and valuable all-sky database.

As detailed below, the xNTD is a very powerful telescope in its own right. It is highly flexible and can be upgraded to larger collecting areas relatively easily. This modular approach is crucial if and when extra funding becomes available.

3 Science Program

As the xNTD is primarily a survey telescope it is envisaged that large survey teams will carry out key projects of relatively long duration. However, a prime consideration for the design of the xNTD is the option for many programs to be carried out in parallel, maximising science output per observing time.

Table 3: Possible H I emission surveys with the xNTD

Survey	Frequency range (MHz)	redshift	Ngal	M* (z)	Area (sq deg)	Time (days)
Shallow	1200 – 1450	0.00 – 0.18	500000	0.13	20600	360
Deep	1000 – 1250	0.14 – 0.42	35000	0.32	120	100
Ultra-Deep	675 – 925	0.54 – 1.10		0.62	30	360

Under such a scheme, the output data would be split and used by several different observing teams each perhaps with their own dedicated software for data analysis.

The xNTD is a low-frequency instrument with three major surveys envisaged.

- Spectral line surveys for H I at cosmologically interesting redshifts.
- Continuum and polarization surveys over the entire sky to high sensitivity.
- High time-resolution surveys for pulsars and other fast transients.

Although the xNTD has less than 1% of the collecting area of the SKA, these surveys enable science drivers which make a start on answering at least some of the questions posed by three of the five KSPs for the SKA as outlined in the introduction. The sections below expand further on the science capabilities of the xNTD.

4 Hydrogen line surveys

Hydrogen is the most ubiquitous element in the Universe. Hydrogen provides the fuel which ignites stars and provides a tracer of galaxies in all stages of their evolution and environments. Its most common form is as neutral hydrogen (H I), which is most easily detected through its hyperfine transition line which has a rest frequency near 1.42 GHz. As such, mapping of the Universe in H I remains the domain of the radio astronomer. Furthermore, the shift of the spectral line from its rest frequency allows a direct measure of the redshift of an object without recourse to extra observing. H I is therefore an amazingly powerful tool for mapping the Universe in both spatial and temporal coordinates.

How galaxies form is one of the key cosmological questions. The generally accepted picture is that galaxies originate within dark matter potential wells, gradually growing from small objects into big ones in a hierarchical fashion through merging or accretion. Although the merging of dark matter halos is reasonably well understood through modelling and numerical simulations, the role of the gas and stars in this process is only poorly known.

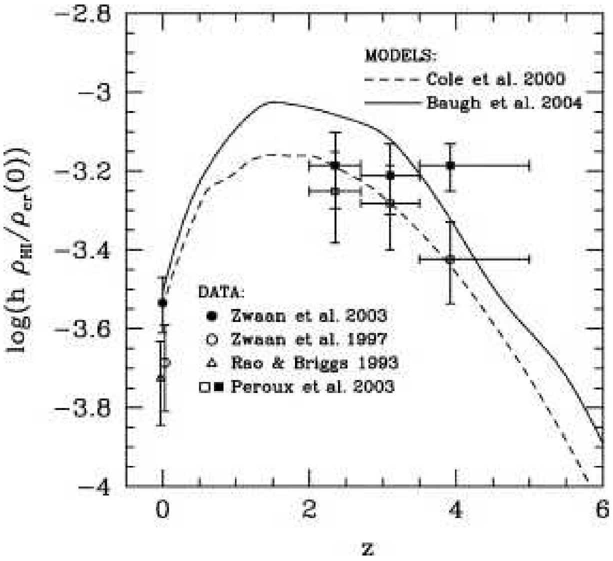

Figure 1: The mass density of H I in units of the present day critical density, as a function of redshift taken from Baugh et al. (2004). Data points near z=0 are from radio surveys; those at redshift 2 and above from optical observations of damped Lyman-α systems. Two model predictions are shown with the solid and dashed lines.

It is well known that there is strong evolution in the star-formation rate, which peaks near z$\sim$2 and has strongly declined by the present epoch. The neutral gas likely evolves in a similar fashion but observational constraints exist only at z$\sim$0 (through H I surveys such as HIPASS) and at z$>$2 (through optical observations of the Lyman-α transitions). Fig 1 shows this in graphical form. Although much of the red-shift range will require the much higher physical collecting area and hence sensitivity of the SKA to address, the low red-shift portion of the distribution, out to about z = 0.25 can be determined by surveys with the xNTD. This is already useful, especially if the evolution is as steep as the models shows in Fig 1 suggest. Blind, volume limited H I surveys provide an optically unbiased probe of all the gas-rich galaxies in the entire volume. Galaxies of low surface brightness and faint dwarf galaxies which are relatively gas-rich, are easily detected in H I surveys, unlike optical surveys. Clustering of galaxies both spatially and in redshift is directly quantifiable in an H I survey.

Although H I emission surveys are provide a powerful tool, going to large redshifts is extremely time consuming and, even then, only the brightest objects can be detected. In contrast, by providing suitable bright background objects, H I absorption can be probed along lines of sight to high redshift sources. H I absorption studies have the potential to test CDM predictions for the mass-assembly history of galaxies by probing the gas content out to z$\sim$1. Damped Lyman-α absorbers (DLAs) have high H I column densities ($N_{HI} \sim 10^{20}$ cm^{-2}) and may be galaxies in the process of forming. Optical DLA studies can only probe above z$>$1.7 leaving the parameter space below this open to radio astronomy. Targetted observations of sources near z$\sim$0.5 have been successful, but only a small handful of site lines have been observed to date (Darling et al. 2004).

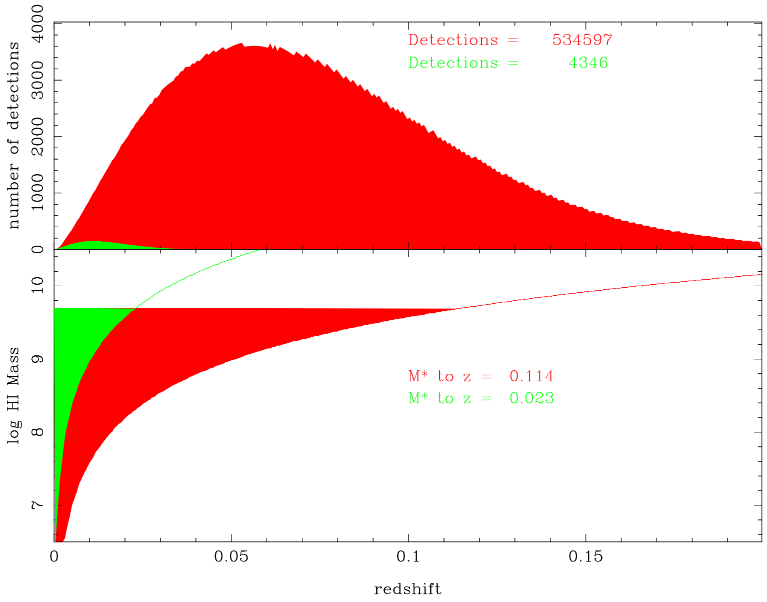

Figure 2: Simulations of H I surveys. The red curve in the top panel shows the number of detections as a function of redshift for an xNTD survey of the entire southern sky taking 1 year observing time. The lower panel shows the detection depth of galaxies of various H I masses. The green curve shows a simulation of the HIPASS survey for comparison.

4.1 Emission line surveys

The 256 MHz instantaneous bandwidth of the xNTD, coupled with an overall total bandwidth of $\sim$1 GHz allows us to envisage 3 possible surveys for galaxies in H I emission ranging from z=0 to z=1. In the simulations that follow, we assume a cosmology which has $H_0 = 75$ kms^{-1}Mpc^{-1}, $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $\Omega_K = 0$, the H I mass function given by Zwaan et al. (1997) and further assume no evolution of the gas as a function of red-shift.

Table 3 gives information for the 3 surveys, described in more detail below. Column 4 (labelled Ngal) gives the total number of galaxies estimated to be detected in the survey. Column 5 * gives the redshift to which M* galaxies will be found. The total survey area and duration are given in the last two columns.

4.1.1 All-sky survey

The current best all-sky survey for galaxies in the H I emission line is the recently completed Parkes Multibeam (HIPASS) survey which detected 4500 galaxies in H I over the entire southern sky with a median velocity of 4500 km s^{-1} (Koribalski et al. 2004; Meyer et al. 2004). The Arecibo survey of the northern sky (ALFA) will reach roughly similar sensitivities. It should be noted that both the Parkes and the Arecibo H I surveys were taken with a single dish whereas the xNTD survey will be an interferometric one. Interferometers are much less susceptible to interference, standing waves, baseline ripple and the

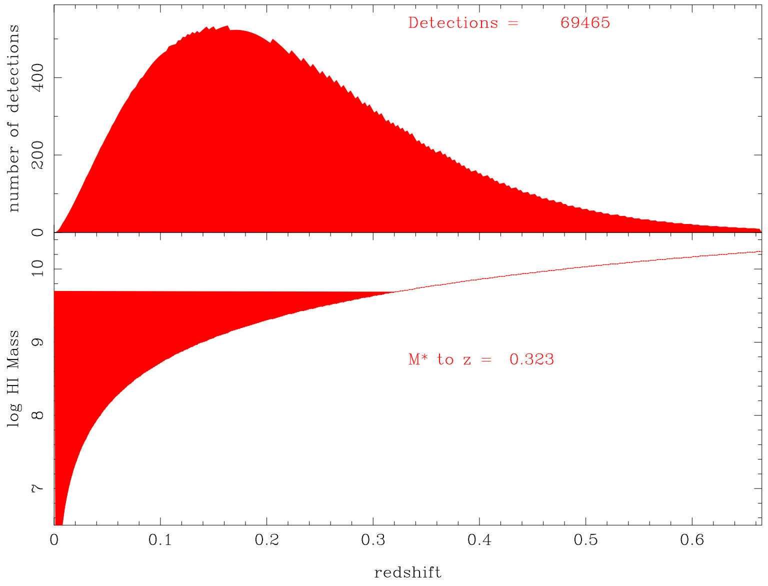

Figure 3: Simulation of a deep H I covering 120 square degrees with 100 days of observing time with the xNTD. For details see Figure 2.

like and hence the xNTD survey is likely to suffer much less from the systematic problems which plague the single dish surveys and worsen their effective sensitivity.

As a minimum requirement, an xNTD survey for H I should exceed the HIPASS survey by at least two orders of magnitude; i.e. it should detect 500,000 galaxies over the entire southern sky, with M* galaxies detectable to at least z∼0.1. Such a survey exploits the entire 256 MHz of instantaneous bandwidth likely available to the xNTD. This survey can be achieved in one year with a 20 element xNTD giving a field of view between 30 and 40 square degrees. Figure 2 shows the total number of detection and the H I mass limit as a function of redshift, compared to the HIPASS results.

Science goals include the determination of the H I mass function for various environments, morphological types and redshift ranges. This requires large numbers of detections in each sub-category which only a huge total sample can provide (cf the 2dF optical surveys) HIPASS, for example, detected more dwarf galaxies in H I than expected, sigificantly improved the mass function at the low-mass end, and gave hints that the mass function varied as function of type. At low velocities, enough galaxies should be detect to allow the large scale structure to be unveiled. Finally, tidal tails, bridges and filaments can be detected in the very nearby objects and these map the history of mergers and gravitational interactions between galaxies.

4.1.2 Deep survey

In order to go further out in redshift, the integration time needs to increase substantially. One can imagine a deep survey to image in the redshift space from 0.14 to 0.42 (frequencies between 1.0 and 1.25 GHz).

The xNTD as originally specified can reach these sort of depths in a survey lasting about 35 days for each pointing. This would detect some 20,000 galaxies per pointing (40 square degrees) with M* galaxies detected out to z∼0.32. Any increase in sensitivity resulting from an upgrade in e.g. the collecting area would be best used by increasing the survey area appropriately.

4.1.3 Ultra-Deep survey

An ultra-deep survey would boldly go where no-one has gone before albeit over a rather small survey area. We could centre our 256 MHz of bandwidth at 800 MHz therefore covering the redshift range from 0.54 to 1.10. This survey would require at least one year of integration time on the same pointing and would be heavily reliant on the rms continuing to decrease over that integration period. Although such a survey is unlikely with the current xNTD specifications, an increase in survey speed by a factor 2 makes the integration time more manageable.

4.2 Absorption line surveys

Optical spectra of quasars show absorption lines known as the Lyman-α forest caused by intervening neutral hydrogen gas between the source and the observer. The intervening gas, with rather low column density (10^{12} to 10^{17} cm^{-2}) either arises in the halos of normal galaxies or in a network of filaments in the intergalactic medium known as the 'Cosmic Web'. Dectecting this low surface brightness gas in the radio is very difficult but it is possible to trace the gas with much higher column density using H I absorption against bright background sources.

The column density, N_{HI} (cm^{-2}), of a cloud is related to its optical depth (τ) and spin temperature T_s (K) via

$$N_{HI} = 1.8 \times 10^{18}\ T_s\ \int \tau\ dV \tag{4}$$

We assume 'typical' parameters for Damped Ly-α Absorbers (DLAs) such that $N_{HI} \sim 2 \times 10^{20}$, $T_s \sim 1000$ K and $V \sim 10$ km s^{-1}. These numbers imply an optical depth near 0.01.

With a 40 square degree FoV, more than 50 objects per pointing would have flux densities in excess of 100 mJy. The majority of these objects are AGN with median redshift z∼1. For a 100 mJy source, we require a 5-σ sensitivity limit of 1 mJy in a channel 10 km s^{-1} wide (50 kHz) in order to detect a line with $\tau \sim 0.01$. This requires 7 days observing per FoV for the xNTD and would yield detectable foreground DLAs towards 4-5 objects. Although this is rather slow going, one could consider doing such a survey in two passes to cover a good redshift range. The first pass could be done with the deep H I emission survey described above and would cover z from 0.14 to 0.42. A further survey could then cover the range out to z∼0.9.

Note that the xNTD will not have the angular resolution to resolve any of the background sources and so direct mapping of the DLAs cannot be attempted; such an experiment is likely the domain of the full SKA.

The absorption survey would certainly benefit from a larger total observing bandwidth to cover as much redshift space as possible in one hit. Any fractional increase in the survey speed through increased collecting area also would cut down the total integration time by a similar fraction.

5 Continuum and polarization surveys

It is important to recognise that, for the xNTD, an all-sky H I survey and an all-sky continuum survey can be carried out in parallel by exploiting the full 256 MHz bandwidth available. Parameters for the two surveys should therefore be complementary to ensure maximum science returns from both surveys. The H I survey described above will yield a 1-σ sensitivity of $\sim$9 μJy (over 256 MHz of bandwidth) across the entire sky. This is extremely sensitive and confusion becomes a major issue at these flux levels. According to Jackson (2004), these sensitivity levels require a resolution of about a few arcsecond at 1.4 GHz to avoid natural confusion. This is the equivalent of baselines of order 10 km. If such a survey can be realised, it would detect in excess of 10^7 sources over half the sky.

Avoiding the confusion in the continuum sets strong constraints on the maximum baseline length. With short baselines, the survey becomes very confused. With long baselines, some H I galaxies may start to become resolved very rapidly, reducing the effective sensitivity of the survey. For computational and storage reasons, Cornwell has pointed out that baselines in the range 1 - 5 km will be the most that the xNTD can aspire to at least in the short term.

5.1 Isotropy

Although observations of the CMB tell us that the Universe was largely isotropic at z$\sim$1100, we do not know what the case is at z$\sim$1 to anything like the same level of precision. Because radio galaxies are at cosmologically interesting distances, it is possible to measure the dipole anisotropy from large scale radio surveys. Measurements of the dipole anisotropy at various redshifts are necessary to establish which gravitational structures responsible for generating the acceleration which leads to the anisotropy, and for establishing that the anisotropy itself is not intrinsic. The NVSS survey gives the tightest constraint currently (Blake & Wall 2002), but the deeper and more uniform xNTD survey would improve this constraint by a least a factor of 4. It would be ideal to complement any xNTD survey with an equivalent in the northern hemisphere.

The 2-point angular correlation function measures how clustered sources are compared to a random (Poisson) distribution. Even without redshifts this simple measure can be used to determine galaxy clustering strengths, trace the radio size distribution of galaxies, independently test AGN unification schemes and map the distribution and clustering of star forming galaxies. A deep survey could also discriminate between various evolution models for AGNs and starburst galaxies. The angular correlation function has been determined from both NVSS and SUMSS surveys but the power of the xNTD survey

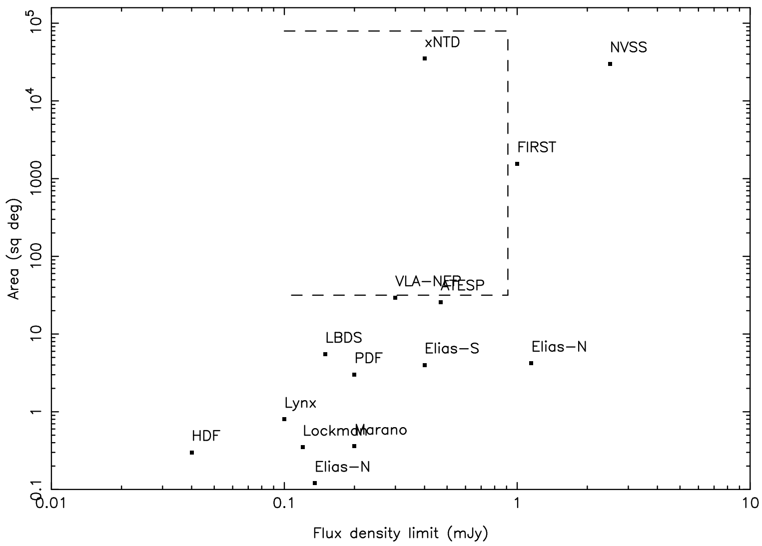

Figure 4: Parameter space for continuum surveys carried out at frequencies near 1.4 GHz. The xNTD survey is nearly an order of magnitude more sensitive than NVSS and covers substantially greater area than other deep surveys. The area enclosed within the dashed lines show unchartered territory.

is its shear statistical size, allowing, for example, significant sub-samples for a range of different radio spectra to be derived.

Finally, it may be possible to detect the Integrated Sachs Wolf (ISW) effect as predicted in the ΛCDM model by comparing the fluctuations detected in the CMB with large scale fluctuations in the mass distribution at z∼1 as probed by radio galaxies. This would answer the question of whether dark energy exists at z∼1 and if so on what scale does it play a role. The NVSS radio galaxies appear to correlate with the microwave sky, but at a significance of only 2-sigma (Boughn & Crittenden 2004). A deeper and more complete survey which the xNTD could provide would produce a much more stringent test of the correlation.

5.2 Polarization and Cosmic Magnetism

The origin of magnetic fields in galaxies and galaxy clusters remains an open question and a key science driver for the SKA. The role that magnetic fields play both in the evolution of galaxies and of the interstellar medium is also poorly understood. Most of what we know about magnetic fields comes via the detection of radio emission; in particular determining the rotation measure of an object gives direct information on the magneto-ionic medium through which its radiation travels. The xNTD can make a start on determining rotation measures for a large number of extragalactic sources, and provide tomographic imaging of small scale structure in the Milky Way.

The large instantaneous bandwidth of the xNTD enables the rotation measure and position angle of polarized radiation to be measured relatively easily at least for strong sources (although ionospheric effects will be important below 1 GHz). Both the all-sky continuum survey and any spectral line surveys would provide polarization information as a natural by-product. A stringent requirement is that the polarization be accurate to at least 1% and probably better across the entire field-of-view, a significant challenge for large field-of-view telescopes. Confusion in polarized flux should not be an issue at these sensitivity levels.

The all-sky survey described above has a 5-σ of $\sim$50 μJy and at this flux level, Beck & Gaensler (2004) estimate there will be spacing between detected polarized sources of about 10 arcmin or about 500,000 sources in the southern sky as a whole. Obtaining reasonably accurate RMs ($\pm$5 rad m^{-2}) can only be achieved at flux levels about a factor of two higher, and not all sources will have measurable RMs. We estimate therefore some 60,000 RM sources across the sky or about 3 per square degree. This number is somewhat conservative as it seems likely that the polarization fraction is higher for the weaker sources (the starbursts) than for stonger sources (AGN).

These RM data could be used to get a complete picture of the Galaxy's magnetic field - especially the vertical field, about which not much is known and is a key discriminant in dynamo models. For objects for which redshift can be determined, this sample would make a start on probing the structure of the inter-galactic magnetic field.

Small scale structure and turbulence in the Milky Way can be probed using Faraday tomography in which foreground gas produces complicated frequency dependent polarization features when viewed against the diffuse background emission. Observations in slices of $\sim$100 MHz from 800 - 1700 MHz would then provide a complete 3-D imaging of the small scale structure in our local neighbourhood. The mapping speed of the xNTD means that all of the southern galactic plane could be imaged in this way. The optimum resolution for such a survey would be $\sim$1 arcmin.

5.3 Variability and Transients

Generally, radio telescopes have high gain and small field-of-view severely limiting the possibility of detecting (random) transient events. Transients can be divided into fast (1 second and less) and slow transients; fast transients will be dealt with in a subsequent section. Slow transients can be detected directly in the u-v plane using the normal data flow through the imaging correlator. Many types of radio transients are known (X-ray binaries, supernovae, magnetic flares from stars and planets, gamma-ray bursts, pulsars etc) although there is still a large phase space to be explored (Cordes & McLaughlin 2004) as shown by the recent detection of transient emission of unknown origin from near the Galactic Centre (Hymen et al. 2005). The good sensitivity and large field-of-view make the xNTD a unique instrument for studying transient emission.

Gamma-ray bursts (GRBs) are an example of transients for which the xNTD can make a lot of progress. There are about 600 GRBs per year and, in the radio, some 25% are expected to remain visible above 0.1 mJy for $\sim$30 days (Carilli et al. 2003). This implies some 75 GRBs per year would be visible by the xNTD in the southern hemisphere and the study of their light curves would thus provide a large increase in our knowledge in the evolution of these sources at late times. It should also be possible to detect GRBs in the radio without the associated γ-ray emission. Current constraints on these objects are rather poor, but one might expect some 200 sources in the sky at any one time out to z$\sim$0.6 and variable over several months (Totani & Panaitescu 2002).

A sub-sample of compact quasars show variability on timescales of less than a day (the IDV sources). This variability is caused by scintillation by structures very nearby in the interstellar medium and is still poorly understood. An xNTD survey could cover the sky every day to a 5σ limit of 2 mJy and this would yield variability at the 2% level for 100 mJy sources and at the 20% level for 10 mJy sources on a daily basis. This is similar to the levels recently achieved in the (targetted) MASIV survey (Lovell et al. 2003) which has now found more than 150 variable sources out of 700 with the added very interesting result that a larger fraction of weaker sources are variable. With 17 sources per square degree above 10 mJy in the sky (Blake et al. 2004), the xNTD variability survey would revolutionise our knowledge in this domain. The most interesting sources show variability on timescale of hours or less. Follow-up of these sources ideally requires dedicated time on an instrument capable of observing up to 10 GHz.

The xNTD could provide a census of radio-loud supernovae in the nearby Universe. These sources have variability timescales of days or weeks, and an xNTD survey which reached 1 mJy detection levels over this period of time could probe out to at least 50 Mpc (Gal-Yam et al. 2005) for this type of event.

6 Pulsars and Fast Transients

6.1 Pulsar surveys

Large-scale pulsar surveys are required to find exotic and rare objects, as witnessed by the discovery of a binary pulsar-pulsar system in late 2003 (Burgay et al. 2003; Lyne et al. 2004). Timing of pulsars in binary systems provide stringent test of gravity in the strong field limit, and timing of millisecond pulsars aims to detect gravitational waves from merging black holes in the distance universe. The current shopping list for pulsar searchers includes a pulsar-black hole binary system, pulsars in the Galactic Centre, millisecond pulsars and sub-millisecond pulsars. Pulsars also are superb probes of the state of the magneto-ionic interstellar medium. Their dispersion measures provide the mean electron density along the line of sight and their rotation measures provide the mean magnetic field.

Historically, pulsar surveys have not been attempted with interferometers and remain the domain of single dish observers. This is because if one coherently samples all the elements of the array, then either the field of view becomes very restricted (phased array mode) or data reduction needs to be carried out for each pixel across the primary beam. The second stumbling block with wide field-of-view, relatively low sensitivity telescopes such as the xNTD is that the integration time on any given part of sky needs to be very long to gain sensitivity. For example, to compete with the Parkes multi-beam survey, the xNTD would need to observe for 3 hrs per pointing. This has two implications; first the entire data set needs to be stored for that length of time and secondly the Fourier Transforms become very long, significantly increasing processing time.

It seems unlikely therefore that a scientifically valuable survey for millisecond pulsars could be carried out by the xNTD in the first few years of operation. Rather, one could survey the entire sky to a sensitivity similar to that of the Parkes multi-beam survey, but only for pulsar periods of $\sim$50 ms and above. This survey would find up to 1000 new pulsars and provide useful information on the low end of the pulsar luminosity function, the distribution of pulsars and provide many more sight lines through the local volume. Specific parameters for a pulsar survey depend heavily on the xNTD parameters and the available computing power; a full estimation of the requirements will be detailed elsewhere.

6.2 Fast transients

Detection of fast transients also suffers from the data rate problem. Sampling at 1 μs over the entire field-of-view leads to a collection of many 10s of Terabytes per second! Such a data rate is not sustainable and it is difficult to imagine real-time data processing (especially when the data need to be de-dispersed).

However, if the configuration of the xNTD were such that half the collecting area was in a compact central region it would be possible to baseband record the data from (at least) the central beam. Searches could then be made for Cerenkov radiation coming from high energy neutrinos impacting the Moon, or for giant pulse emission from young pulsars.

7 Other Science Programs

7.1 Very Long Baseline Interferometry (VLBI)

The Australian VLBI network will be upgraded with the move to 1 Gbit/s links between the telescopes in the very near future. This will enable bandwidths of up to 128 MHz to be used rather than the 20 MHz in use today. A large collecting area telescope in Western Australia would provide a further significant upgrade to the Australian VLBI network. However, the xNTD is not currently scoped above 1.7 GHz, and therefore cannot reach the important VLBI frequencies at 2.4, 4.8 and 8.4 GHz. Furthermore, to exploit the wide field-of-view of the xNTD it would be necessary to also have a bigger field-of-view on at least one east coast large dish.

The wide field-of-view of the xNTD coupled with mas resolution leads to a phenomenal number of pixels and clearly such data could never be processed. However, the number of sources of interest in any given field is very small and one could envisage only processing the pixels which have signal present. The benefit of wide fields is that there will always be an in-field calibrator(s), allowing phase coherent integration. Science applications include the relative motions of objects in the field (e.g. core-jet motions) and looking at the perennial problem of whether the AGN phase precedes the starburst phase or vice-versa.

Measuring pulsar proper motions can be done at 1.7 GHz using the long, cross-continent baselines. Because pulsar spectral indicies are generally steep, low frequencies are best if good resolution can be obtained. Brisken et al. (2000) using the VLBA, has developed techniques for dealing with ionospheric effects at low frequency and has successfully measured a dozen or so pulsar proper motions with up to 100 pulsars planned for the near future. Using the east coast telescopes plus the xNTD could result in proper motions being obtained for several tens of pulsars in the southern hemisphere (cf only 6 now).

7.2 OH Megamasers near z$\sim$1

OH megamasers are found in galaxies with the highest far-infrared (FIR) luminosities. In turn, these highly luminous FIR galaxies likely originate from strongly interacting or merging galaxy systems and observations of these FIR galaxies can determine the merger rate as a function of z. A search for OH megamasers in high z objects potentially yields information on the merger rates of galaxies and the conditions necessary for maser formation.

The xNTD makes an ideal instrument to survey for OH megamasers around z$\sim$1 in a blind survey. Darling & Giovanelli (2002) argue that with a 3 σ sensitivity of 0.25 mJy one should expect to find a few OH megamasers per square degree per 50 MHz bandwidth interval. To achieve this sort of sensitivity requires 5 days of xNTD time. A 100 day survey would cover 1000 square degrees and could potentially discover more than 1000 OH megamasers at cosmologically interesting distances.

7.3 Galactic H I surveys

The recently completed southern galactic plane survey (SGPS) used the ATCA to image the galactic plane with 2.6 K rms (in the line) at a spatial resolution of 2 arcmin and a velocity resolution of 0.8 km s^{-1} (McClure-Griffiths et al. 2001). The survey covered 100 degrees of galactic longtude and 3 degrees of latitude and took 40 days of observing time. Currently, an all-sky survey with the Parkes multibeam is being carried out to a 1-sigma limit of 70 mK with a mapping speed to 30 square degrees per hour albeit at a resolution of only 14 arcmin.

Surface brightness sensitivity depends critically on the resolution of the instrument. Potentially the best configuration for the xNTD is to have a very compact inner core containing half the collecting area with the remaining collecting area on longer baselines. Such a configuration could yield an ‘inner’ beam of 3 arcmin and a beam of 45 arcsec using the entire array.

A survey of the galactic plane at high resolution would be extremely valuable scientifically. It would be ideal for applications like HI absorption, tracing the small scale turbulence, and studying the interaction of SNRs and HII regions with the gas. In 100 days of observing, 600 square degrees of the galactic plane can be mapped to a depth of 1 K and a resolution of 40 arcsec.

At high galactic latitudes, a deep survey is necessary to unveil the structure of the interstellar medium, with an rms of at least 100 mK required. The impetus for such a survey would be to determine whether the halo is made up of discrete structures (clouds) or whether it is generally smooth. Furthermore, the disk-halo interaction is important for the distribution of heavy elements as metal-enriched material is ejected through galactic ‘fountains’. Also, high latitude surveys would likely detect many high velocity clouds, whose nature still remains unclear. However, the combination of high resolution and good brightness sensitivity over a large area is very difficult to achieve without substantial amounts of collecting area. The xNTD can cover the sky at 2.7 square degrees per hour to a sensitivity of 100 mK at a resolution of 3 arcmin (assuming half the collecting area is in an inner core).

Finally, there are many large structures in the galactic plane which currently take a long time to image as many pointings of the ATCA are required to cover the region. The xNTD would be very good for imaging these structures.

7.4 Magellanic H I surveys

The Large and Small Magellanic Clouds are gas rich dwarf irregular galaxies located at a distance of only 50 kpc. The galaxies are connected in H I via the Magellanic bridge. The Magellanic stream is a very extended halo of H I gas trailing the Clouds and subtending an area of at least 1000 square degrees across the southern sky and there is a further H I arm leading the Clouds (Putman 2000). Generally, these features have only been imaged at low (single-dish) resolution except for small targetted areas at high resolution (Muller et al. 2004, Bruens et al. 2005). High resolution images of the entire Magellanic system are required to fully understand the structure, formation process and turbulence characteristics of this unique system.

The large FoV of the xNTD makes it ideal for such a study; however the low column density of H I in the stream implies that deep integrations will be required to obtain the sensitivity required ($\sim 10^{17}$ cm^{-2}). It would likely take ∼300 days of xNTD time to complete a 1000 square degree survey. This science would benefit strongly from increased sensitivity.

8 Summary

There is no doubt that the xNTD will change our knowledge of the H I Universe. The shallow survey will find an unprecedented number of galaxies across the entire southern sky and the ultra-deep survey has the potential to detect H I galaxies at $z \sim 1$. Vast numbers of continuum and polarized sources will enable cosmological tests and start to unveil the origins of cosmic magnetism. Our knowledge of the transient radio sky will be enabled with the wide field of view that the xNTD offers.

In the northern hemisphere, the (full) ATA will have an almost identical survey speed to the xNTD. The ATA could therefore do a very similar shallow survey to hence achieve true full-sky coverage and eliminate any potential problems with cosmic variance. In the southern hemisphere, the South African KAT is likely to be an instrument with similar sensitivity to the xNTD. Collaboration would therefore be very useful to avoid duplication of effort. One could imagine splitting up the sky between the two groups to improve efficiency, or having the two arrays with very different configurations (one compact, one extended) to cover all the science requirements.

Upgrade possibilities are currently being explored if and when other funding becomes available to the xNTD project. We note that the xNTD has a factor of 25 less collecting area than the Phase I (10%) SKA and is restricted in frequency space relative to that design.

Upgrade paths therefore include some or all of: increased field of view, increased collecting area, cooling of the receivers, increased bandwidth and expanding the available frequency range. The surveys listed in Table 3 require substantial amounts of observing time. Any increase in survey speed over the nominal xNTD parameters would enable a corresponding decrease in integration time.

Adding more collecting area and increasing the upper frequency would appear to benefit the science most at this stage. Increasing the collecting area not only improves the uv coverage and the imaging capabilities but it also greatly enhances the prospects of pulsar surveys and low surface brightness imaging. Increasing the upper frequency limit improves the science in the domain of VLBI, cosmic magnetism and the study of the IDV sources.

Endnote

This document is a DRAFT and remains a work in progress. Any comments, ideas for images and extra input is much appreciated.

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