Surveys with the xNTD and CLAR

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Abstract

We compare strawman designs for two Square Kilometre Array demonstrators, the Extended New Technology Demonstrator (xNTD) and the Canadian Large Adaptive Reflector (CLAR), in the context of survey capability and suitability for addressing key survey science programmes. We first show that, all else being equal, the survey speed for detecting point sources is proportional to the product of field-of-view and the square of the effective collecting area for both interferometer and single-antenna designs. For extended emission, the survey speed is proportional to field-of-view alone for single-antennas, and field of view times the square of the filling factor of the array for interferometers. CLAR offers a very large collecting area, but a small field of view and only modest resolution. xNTD offers the converse, with only moderate collecting area but a large field of view and high resolution. Based on strawman specifications, the two instruments are comparable in speed for point source surveys, with filling factor obviously impacting xNTD for extended emission. However, practical considerations such as spectral baseline removal and continuum confusion likely mean that although the two instruments would be closely comparable for H I galaxy redshift work, xNTD would be far superior for continuum point-source work because of the lower confusion limit in its smaller (synthesised) beam. The large, filled aperture of CLAR would, however, make it the instrument of choice for detecting the cosmic web, and for pulsar work. From a science point of view the two instruments are thus largely complementary.

1 Introduction

The Extended New Technology Demonstrator (xNTD) and the Canadian Large Adaptive Reflector (CLAR) are technology demonstrators for the Square Kilometre Array (SKA) planned by the Australian and Canadian communities respectively. Although they both employ focal plane array technology and will operate over a similar frequency range, they are fundamentally different concepts. CLAR consists of a single element with large collecting area and hence has excellent instantaneous sensitivity over a small field of view. The xNTD is an interferometer made up of medium sized elements with rather poor instantaneous sensitivity which is offset by having a very large field of view. Both concepts therefore have very high survey speeds, orders of magnitude higher than current instruments.

The purpose of this document is as follows. First we outline both systems and their respective parameters. Secondly, we provide a frame work in which to compare survey speeds for different instruments. We include both point source and surface brightness sensitivity calculations. This allows us to compute their survey speeds for the two instruments for continuum, spectral line, and surface brightness surveys. We briefly outline possible scientific applications with each instrument, comparing and contrasting the benefits and drawbacks of the different designs. Finally we summarise our findings.

2 Overview and System Parameters

The New Technology Demonstrator (NTD) is a proposed Australian concept for the design of the Square Kilometer Array (SKA). The key concept behind the NTD is to demonstrate wide field-of-view operations on a $\sim$15 m parabolic dish using a large ($\sim$100 element) focal plane array. The NTD is fully funded through the Major New Research Facility (MNRF) program initiated by the Australian Federal Government.

The xNTD, is an upgrade of the NTD designed to be a front-line scientific instrument in its own right. It builds upon the deliverables from the NTD program and other MNRF projects and benefits from international collaborations with other interested parties. The xNTD will consist of 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.

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 ...'. Although the collecting area of the xNTD is less than 1% that of the SKA, its design and location ensure a modular upgrade path towards the low frequency part of the Phase I SKA and the full SKA is reasonably straightforward provided the technical challenges can be met.

The Large Adaptive Reflector (LAR) is a Canadian design concept that has been proposed as a technology solution for the SKA. It is a revolutionary new concept for building large radio telescopes at extremely low cost per square meter of aperture. The LAR concept incorporates a large-diameter (D$>$150 m), large focal-ratio (f/D$\sim$2.5, giving f$>$375 m) reflector. Instead of using a conventional single mount point, the LAR design supports the near-flat reflector over its entire surface, and relies on actuators to adjust the surface shape and the pointing direction. An airborne phased-array feed is positioned at the focus, and provides multiple beams to image a patch of sky simultaneously.

The Canadian Large Adaptive Reflector (CLAR) is a proposed long-wavelength telescope ($\lambda > 17$ cm) that employs the LAR concept with a 300 m diameter reflector and an 8000-element phased array feed to yield a field of view of 0.3 square degrees. Proof-of-concept experiments are underway, funded through Canadian Federal programmes providing money to National Research Council Canada and Canadian

Table 1: Possible system parameters for the xNTD and CLAR

Parameter	xNTD	CLAR
Number of Dishes	20	1
Dish Diameter	15 m	300 m
Total collecting area	3534 m^2	70700 m^2
Aperture Efficiency	0.8	0.7
System Temperature	50 K	50 K
Number of receiving elements	2000	8000
Field-of-view at 1.4 GHz	40 deg^2	0.3 deg^2
Frequency range	$700 - 1700$ MHz	$700 - 1700$ MHz
Instantaneous Bandwidth	256 MHz	256 MHz
Maximum baseline	3000 m	
Resolution	12 arcsec	150 arcsec
Approximate budget	EUR 18.6M	EUR 29.1M

universities, with industry partners also participating. SKA/LAR has been adopted as a project by the Association of Canadian Universities for Research in Astronomy (ACURA). In 2005 an MOU between ACURA, NRC, and industry has established the Canadian SKA Consortium to develop and direct SKA/LAR work in Canada. The Consortium receives advice on scientific issues from the Canadian SKA Science Advisory Committee, a sub-committee of the CASCA Radio Astronomy Committee. In 2004 the predecessor of CSSAC published the CLAR science case.

The likely parameters for the xNTD and CLAR telescopes are given in Table 1. These parameters should be considered as preliminary only; they are likely to undergo modifications as the technical specifications (and cost) become better known. The current estimate of the budget for the xNTD is $\sim$AUD\$30 M (EUR 18.6M) and that for CLAR at $\sim$CAD\$40 M (EUR 29.1M). We make no allowance for the cost difference in this document.

3 Survey sensitivity

Here we consider the speed of a given (large-area) survey for both point source sensitivity (in mJy) and in brightness sensitivity (in K). We consider the single antenna case and the correlating interferometer. Table 2 lists the definitions used in this section.

Table 2: Symbol definitions

σ_s	point source rms in flux density units	σ_t	surface brightness rms in Kelvin
B	bandwidth	t	integration time
k	Boltzmann constant	T	system temperature
θ	beam size	Ω	beam solid angle
D	diameter of one element	A	area of one telescope element
N	number of elements	F	field of view
SS_s	point source survey speed	SS_t	surface brightness survey speed
f	filling factor	L	length of longest baseline
n_p	number of polarizations	λ	observing wavelength
ϵ_a	aperture efficiency	ϵ_c	correlator efficiency
ϵ_s	synthesised aperture efficiency		

3.1 Survey resolution

3.1.1 Single Antenna case

The resolution of a single antenna is given by

$$\theta = \frac{\lambda}{D\ \sqrt{\epsilon_a}} \tag{1}$$

3.1.2 Interferometer case

The synthesised beam of an interferometer (and hence the resolution) can be expressed as

$$\theta = \frac{\lambda}{L\ \sqrt{\epsilon_s}} \tag{2}$$

where ϵ_s is a 'synthesised aperture efficiency' (cf equation 1 above) which is related to the weighting of the visibilities and is always ≤ 1.

3.2 Point source survey sensitivity

3.2.1 Single Antenna case

The point source sensitivity is given by

$$\sigma_s = \frac{2\ k\ T}{A\ \epsilon_a\ \epsilon_c\ \sqrt{n_p\ B\ t}} \tag{3}$$

Re-arranging to give the time to achieve the required sensitivity

$$t = \left(\frac{2\ k\ T}{A\ \epsilon_a\ \epsilon_c}\right)^2 \frac{1}{\sigma_s^2\ B\ n_p} \tag{4}$$

Let the antenna have a field of view which covers F square degrees of sky. Then the number of square degrees per second you can survey to a given sensitivity limit is $SS_s = F/t$ or

$$SS_s = F\ B\ n_p \left(\frac{A\ \epsilon_a\ \epsilon_c\ \sigma_s}{2\ k\ T}\right)^2 \tag{5}$$

with all units in SI.

3.2.2 Interferometer case

The point source sensitivity is given by

$$\sigma_s = \frac{\sqrt{2}\ k\ T}{A\ \epsilon_a\ \epsilon_c\ \sqrt{0.5N(N-1)\ n_p\ B\ t}} \tag{6}$$

which can be simplified in the case of large N to

$$\sigma_s = \frac{2\ k\ T}{A\ N\ \epsilon_a\ \epsilon_c\ \sqrt{n_p\ B\ t}} \tag{7}$$

Re-arranging to give the time to achieve the required sensitivity

$$t = \left(\frac{2\ k\ T}{A\ N\ \epsilon_a\ \epsilon_c}\right)^2 \frac{1}{\sigma_s^2\ B\ n_p} \tag{8}$$

Let the interferometer have field of view which covers F square degrees of sky. Then the number of square degrees per second you can survey to a given sensitivity limit is $SS_s = F/t$ or

$$SS_s = F\ B\ n_p \left(\frac{A\ N\ \epsilon_a\ \epsilon_c\ \sigma_s}{2\ k\ T}\right)^2 \tag{9}$$

with all units in SI.

3.3 Surface brightness survey sensitivity

3.3.1 Single Antenna case

Using the Rayleigh-Jeans approximation, the surface brightness sensitivity is given by

$$\sigma_t = \frac{\lambda^2}{2\ k\ \Omega}\ \sigma_s \tag{10}$$

We can use σ_s from equation 1 to obtain

$$\sigma_t = \frac{T\ \lambda^2}{A\ \epsilon_a\ \epsilon_c\ \Omega\ \sqrt{n_p\ B\ t}} \tag{11}$$

Noting that $\Omega A \epsilon_a = \lambda^2$ then

$$\sigma_t = \frac{T}{\epsilon_c\ \sqrt{n_p\ B\ t}} \tag{12}$$

Re-arranging to give the time to achieve the required sensitivity

$$t = \left(\frac{T}{\epsilon_c\ \sigma_t}\right)^2 \frac{1}{B\ n_p} \tag{13}$$

Let the antenna have field of view which covers F square degrees of sky. Then the number of square degrees per second you can survey to a given sensitivity limit is $SS_t = F/t$ or

$$SS_t = F\ B\ n_p \left(\frac{\epsilon_c\ \sigma_t}{T}\right)^2 \tag{14}$$

with all units in SI. Note the similarities in form between equations 14 and 5, apart from the antenna gain terms.

3.3.2 Interferometer case

As before, using the Rayleigh-Jeans approximation, the surface brightness sensitivity is given by

$$\sigma_t = \frac{\lambda^2}{2\ k\ \Omega}\ \sigma_s \tag{15}$$

We can use σ_s from equation 4 to obtain

$$\sigma_t = \frac{T\ \lambda^2}{A\ N\ \epsilon_a\ \epsilon_c\ \Omega\ \sqrt{n_p\ B\ t}} \tag{16}$$

We can define the 'filling factor', f, to be the amount of effective collecting area inside a circle of diameter L (equivalent to the maximum baseline length). Thus

$$f = \frac{A \ \epsilon_a \ N}{\frac{\pi}{4} L^2} \tag{17}$$

By using equation 2, and also noting that

$$\theta^2 = \frac{\pi}{4} \ \Omega \tag{18}$$

we can re-arrange to show

$$L^2 = \frac{\lambda^2}{\frac{\pi}{4} \ \Omega \ \epsilon_s} \tag{19}$$

and so

$$f = \frac{A \ \epsilon_a \ N \ \Omega \ \epsilon_s}{\lambda^2} \tag{20}$$

Finally then,

$$\sigma_t = \frac{T \ \epsilon_s}{f \ \epsilon_c \ \sqrt{n_p \ B \ t}} \tag{21}$$

Re-arranging to give the time to achieve the required sensitivity

$$t = \frac{1}{B \ n_p} \left(\frac{T \ \epsilon_s}{f \ \epsilon_c \ \sigma_t} \right)^2 \tag{22}$$

Let the interferometer have field of view which covers F square degrees of sky. Then the number of square degrees per second you can survey to a given sensitivity limit is $SS_t = F/t$ or

$$SS_t = F \ B \ n_p \left(\frac{\epsilon_c \ \sigma_t}{T} \right)^2 \ f^2 \ \epsilon_s^{-2} \tag{23}$$

with all units in SI.

3.4 Summary

In summary, the survey speed for point sources, all else being equal, is

$$SS_s \propto F \ (A \ N \ \epsilon_a)^2 \tag{24}$$

with $N = 1$ in the single dish case. The survey speed for surface brightness observing, all else being equal, is

$$SS_t \propto F \, f^2 \tag{25}$$

with $f = 1$ in the single dish case. In the interferometric case, the definition of f in equation 17 then implies that, for a given L, $SS_t \propto F \ (A \ N \ \epsilon_a)^2$ (as for equation 24) and we can see that for surveys generally, the speed is proportional to the field-of-view times the square of the effective collecting area.

Table 3: Survey speeds for the xNTD and CLAR

Survey	xNTD	CLAR	
Continuum survey speed	2800 deg^2/hr	6400 deg^2/hr	256 MHz, 0.3 mJy rms
Line survey speed	60 deg^2/hr	140 deg^2/hr	5 kHz, 10 mJy rms
Surface brightness survey speed		44 deg^2/hr	5 kHz, 0.1 K rms, $2.5'$ resolution
Surface brightness survey speed	0.001 deg^2/hr		5 kHz, 0.1 K rms, $12''$ resolution

Table 3 gives an overview of the survey speeds of the two instruments. We consider three surveys with different parameters, listed in the final column of the table. The first survey is a continuum survey which uses 256 MHz of bandwidth and achieves an rms of 0.3 mJy. The second survey is a spectral line survey which aims to achieve 10 mJy rms in a single 5 kHz channel. The final survey is a surface brightness survey to achieve 0.1 K rms in a 5 kHz channel. Note that the survey speed here is highly dependent on the resolution which is significantly different for both instruments. For continuum and line surveys, CLAR is somewhat more than a factor of 2 faster than xNTD. For surface brightness surveys, the filled aperture of CLAR makes if significantly better than the xNTD but at the expense of $2.5'$ resolution.

As a point of reference, the all-sky NVSS had a survey speed of 42 degrees per hour to a sensitivity limit of 0.3 mJy for point sources. The spectral line surveys using the Parkes multibeam receiver could survey at 2.4 degrees per hour to achieve 10 mJy sensitivity over 5 kHz. Both CLAR and xNTD better these by more than an order of magnitude in both the point source and spectral line domain.

4 Science Program

The xNTD and CLAR are low-frequency survey instruments with three major scientific drivers.

- 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.

Although xNTD and CLAR have significantly less collecting area than the eventual SKA, these surveys dovetail nicely with three of the five ‘Key Science Projects’ as identified in ‘Science with the Square Kilometre Array’ [New Astronomy Reviews, v48, 2005] viz ‘Galaxy evolution, cosmology and dark energy’ [Rawlings et al., p1013], ‘The origin and evolution of cosmic magnetism [Gaensler et al., p1003] and ‘Strong field tests of gravity using pulsars and black holes’ [Kramer et al., p993]. The two remaining

Key Science Projects, 'The cradle of life' [Lazio et al., p985] and 'Probing the Dark Ages' [Carilli et al., p1029] require observing frequencies outside those proposed for xNTD and CLAR.

In this section, we outline the prospects for various surveys. For full details of the science outcomes of such surveys and possible other science applications with these telescopes we refer readers to other documents.

4.1 H I emission surveys

An extragalactic survey of the entire sky contains valuable information on the distribution of galaxies, the H I mass function, the dynamics of groups and the frequency of dwarf galaxies. Such a survey is unbiased in terms of tracing large-scale structure, especially as it can detect galaxies optically hidden behind the plane of our own Galaxy. H I galaxies are not bright, only 30 galaxies have been detected beyond $z = 0.1$ to date and there are less than 10 known at $z > 0.2$. The evolution of H I gas as a function of time is therefore currently poorly constrained but is vital for understanding the gas evolution in the Universe.

There are two main differences between an H I emission survey with the xNTD and CLAR. First, the xNTD will have significantly better positional accuracy than CLAR. With a resolution of 12 arcsec, positional accuracy will typically be better than 5 arcsec. This is sufficient to unambiguously identify the galaxy in the optical, even without velocity information. With the resolution of CLAR of 150 arcsec there will not always be a certain optical identification. Secondly, it is likely that the noise will be better behaved in the case of an interferometer than with a single dish instrument. Problems such as baseline ripple, solar interference and continuum subtraction are significantly reduced in the interferometric case. The Parkes HIPASS survey, for example, did not detect galaxies down to its theoretical limit because of these and other issues. Some of these problems may be reduced in the case of CLAR because of the extra information coming from the focal plane array but they will not entirely be eliminated. CLAR also has a cos(Zenith Angle) dependence in sensitivity because of the decrease in projected collecting area. The aperture efficiency used here includes an all-sky coverage of this effect. In practice, actual sensitivity achieved will depend on ZA, and while observing techniques can minimize the impact on the data, it is inevitable that the sensitivity of the instrument will be position dependent.

We consider two possible surveys. The first has a duration of 1 year and covers 20000 square degrees of sky. The second also has 1 year duration but covers only 40 square degrees of sky. We use 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. [ApJ, v490, p173, 1997] and assume no evolution as a function of red-shift.

Near-identical survey results are achieved by setting detection limits at 5-sigma for xNTD and 8-sigma for CLAR; the latter number is reasonable in light of the caveats discussed above. The all-sky survey detects about 10^6 galaxies with M_* galaxies detected out to $z \sim 0.1$. The deep survey detects $\sim 10^5$ galaxies with M_* galaxies detected out to $z \sim 0.6$ and a significant number of galaxies out to $z \sim 1$.

4.2 Continuum and polarization surveys

The detection of many millions of radio galaxies opens the door to a number of cosmological tests including possible detection of the dipole anisotropy, discriminating between various unification and evolution models, and detection of the integrated Sachs-Wolf effect and tests of dark energy.

CLAR has only a modest resolution, 150 arcsec, and will therefore reach the confusion limit for this beam size after only a short integration time. As the beam size is already significantly larger than in other large surveys such as NVSS, CLAR will not add significantly knowledge of the continuum sky. It may however be sensitive to low surface brightness extended objects largely missed by previous surveys if the confusion problem can be overcome. In contrast, the xNTD with 12 arcsec resolution (about one quarter that of NVSS) is able to reach the confusion level of $\sim$10 μJy over the entire sky after 1 year of observing. This survey would be a natural by-product of the large area H I survey described above. Such a survey would detect in excess of 10^7 sources with a median redshift in excess of 1. Furthermore, the good positional accuracy will enable the radio database to be cross-correlated with deep spectroscopic optical and infra-red surveys thus identifying which types of galaxies are associated with particular radio selected samples.

A natural outcome of this type of survey is polarization information on all the sources detected. Well in excess of 10^5 sources are expected to have sufficiently strong polarization to allow determination of their rotation measures. This enables a RM grid with an average spacing between sources of 10 arcmin to be created over the entire sky creating a powerful tool for studying the global magnetic field structure of the Universe and individual cluster sources. While the xNTD will be ideal of these purposes, CLAR will also be of value because the confusion limit in Stokes Q and U is significantly less than in Stokes I. The xNTD will largely resolve out the foreground (galactic) polarized structures whereas CLAR will be capable of producing RM maps across these extended faraday screens.

There are a number of caveats here which deserve mention. First, the high resolution coupled with a large field of view severely taxes the correlator and the computing power required to both produce, calibrate and store the resultant data cubes. Secondly, to reach $\sim$10 μJy across the entire sky requires dynamic range of at least 10^4. Whether this can be achieved with the xNTD is yet to be determined. Both these issues may force the baselines to be shorter than 3 km. Finally, to maintain polarization purity over a very large field of view is a major challenge and one that both CLAR and xNTD would need to overcome to ensure the success of the polarization survey.

4.3 Pulsar surveys

Over the past two decades, pulsar observers have used large single dish telescopes to perform their surveys, most recently with multiple feeds to efficiently re-use the collecting area. Surveys with interferometers, while possible, are extremely computing intensive unless incoherent addition (and subsequent loss of signal to noise) techniques are used. Recently, WSRT has been used in its grating mode configuration to search for pulsars; the presence of multiple identical baselines significantly cuts down on the computing power required.

CLAR is a much more efficient instrument for pulsar searches than the xNTD, unless the xNTD was also arranged in a grating configuration. The advantages of CLAR are two-fold. First, the overall computing and storage requirements are orders of magnitude smaller for CLAR than for xNTD. For CLAR, one merely has to record the outputs from the various focal plane array elements whereas for the xNTD one has to pixelise the entire primary beam at 12 arcsec resolution. Secondly, the high instantaneous sensitivity of CLAR implies that relatively short integration times are required to detect faint pulsars. This is not the case with the xNTD where very long integrations are required. These long integrations significantly increase the computing power required to process the data. The combination of these two effects make a pulsar survey with the full xNTD out to a 3 km baseline almost impossible to envisage in the near-term.

A survey with CLAR, if it had access to the Galactic Centre and negative Galactic longitudes, would detect several thousand pulsars, doubling the sample of known pulsars. Such a sample would likely contain many exotic objects, including millisecond pulsars, relativistic binary pulsars and pulsars orbiting black holes. Furthermore, the high instantaneous sensitivity of CLAR makes it an ideal instrument for timing the pulsars once they have been discovered.

4.4 The Cosmic Web

The so-called Cosmic Web is an intricate network of gaseous filaments and sheets in the inter-galactic medium predicted by numerical models of structure formation in a cold dark matter Universe. It is believed to be responsible for the Ly-α absorption lines seen in quasar spectra, but has never been detected directly: detection limits for these filaments in the optical and X-ray are orders of magnitude below current capabilities, and, in the radio, H I in emission is also very difficult to detect as the column densities are very low, below 10^{18} cm^{-2}.

Imaging the Cosmic Web and tracking its evolution and structure as a function of redshift are key to understanding the formation history of galaxies and clusters of galaxies. A filled aperture such as CLAR is needed to detect the expected low surface brightness features. A deep survey with CLAR has the potential to reach a detection limit of $\sim 10^{16}$ cm^{-2}, allowing the denser neutral gas in the Cosmic Web to be imaged in emission for the first time. Significantly, this will allow the detection of such gas anywhere of the sky rather than only on limited sight-lines to quasars. CLAR will also be able to detect extended galaxy disks and haloes, and damped Ly-α systems, which are believed to be galaxies in formation.

The long baselines of the xNTD mean that it cannot detect H I in emission at these low column densities. However, it will be a powerful instrument for detecting H I in absorption against background quasars up to z$\sim$1 (a redshift regime not observable using the optical Ly-α lines) across the entire sky. This is a complementary tool for understanding gas evolution at higher redshifts than possible for the H I emission survey, but is limited to sight-lines to luminous objects.

5 Conclusions

We have written out a formalism that allows survey speeds to be computed for single dish and interferometric system. We have shown that, given the current straw-man specifications for both CLAR and xNTD, the survey speed of CLAR for continuum and spectral line surveys is a factor of 2 better than that of xNTD. For surface brightness sensitivity, the filled aperture of CLAR makes the survey speed significantly higher than the sparse xNTD interferometer, albeit at rather modest resolution.

For spectral line surveys both instruments have very high survey speeds compared to current instruments and will detect huge numbers of H I galaxies at significant redshifts. The low resolution of CLAR means it will be confusion limited making the xNTD the superior instrument for continuum surveys; it will detect 10^7 objects down to a confusion limit of 10 μJy and detect polarized sources in large numbers as a start to creating an all-sky RM grid. For pulsar surveys, CLAR is an ideal telescope and will detect and time many thousands of new pulsars. CLAR can also map the Cosmic Web and other low surface brightness features to unprecedented sensitivity.

There are still large technical, computing and economic challenges to be met before completion of CLAR and the xNTD. It is still very early days in the application of focal plane array technology to radio astronomy. Issues such as the stability of the primary beam, achieving large dynamic range and polarization purity need to be established. Computational complexity both on-line (beam formers and correlators) and off-line (image calibration and processing) are major challenges for wide field of view imaging. The cost of the collecting area remains a major issue for the SKA in general. Finally, the issue of radio frequency interference (RFI) and how best to mitigate it remains important for the SKA and its design. Even though the sidelobes of the smaller xNTD antennas will have higher amplitude than CLAR, an interferometer offers intrinsic RFI rejection, because weak RFI from the well outside the field being imaged will not correlate. The airborne feed of CLAR will have direct sightlines to a large area, and will require adaptive nulling using the phased-array feed to eliminate any interfering signals.

The scientific benefits of both xNTD and CLAR are obvious and they are in many senses complementary instruments. Either or both will have high impact in cosmology, pulsars and H I science. It is likely that engineering difficulties, cost benefit analysis and funding streams will eventually determine which of the many SKA design concepts will prevail.