Part 11

The Future – Where to go ?

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Studying pulsars with the SKA and other new facilities

Jon Bell
ATNF, CSIRO, PO Box 76 Epping NSW 1710 AUSTRALIA;
jbell@atnf.csiro.au

Abstract. The Square Kilometre Array (SKA) is a proposed next generation radio telescope. Between now and 2005 this project is in a technology development and prototyping phase, with construction likely to begin in ~ 2010. This paper describes what the SKA may be like, its key features, the motivation for building it and where you can access more details about it. Its is important to see any new facility in context, so other new facilities are also discussed. Avenues for future extensibility of the SKA other telescopes are covered, with some emphasis on multiple beam systems. Some suggestions for useful pulsar experiments and pulsar searches strategies are summarised. A conclusion is that the SKA may not be the most cost effective way to search for pulsars and that a 128 beam receiver system on an Arecibo like telescope working between 1 and 5 GHz may be a more cost effective approach.

1. Astronomers Dreams

To meet the goals outlined in the SKA science case (available on www.ras.ucalgary.ca/SKA), astronomers have drafted the following specifications for the SKA:

Frequency coverage	0.2 – 20 GHz
Collecting area	1,000,000 m^2 ($A_e/T_{sys} = 2 \times 10^4$)
Simultaneous frequency bands	$\geq$2
Resolution at 1.4 GHz	0.1 arcsec
Field of view at 1.4 GHz	$1^0 \times 1^0$
Number of simultaneous beams	100

This is a subset of the more detailed specifications which are available on the various SKA web pages listed in Section 8. The specifications are being refined as the science case is refined and it is not too early for people to be contributing their ideas to the science case.

2. Potential Construction Methods

The proposed construction methods may be of some interest to astronomers, because they lead to considerably different capabilities. Existing large radio telescopes like Jodrell Bank, Bonn and Parkes cost thousands of dollars per square metre to build. To be realistic, the total costof the SKA has to be no more that 1 Billion US dollars. This implies then that the collecting area of the telescope has to be built for 200-300 million dollars or ~\$200 per square metre. This section summarises some of the methods proposed for achieving this. More details are on the SKA web pages listed in Section 8.

KARST (China) 10–14 dishes of 300–500m in diameter like Arecibo. The aim being to take advantage of naturally occuring holes in the ground of suitable shape. Substantially improved sky coverage would be obtained by only using part of the dish (at any one time) which is dynamically deformed to focus on a vastly more mobile feed system. Greatly improved sensitivity by using multiple beam feed/receiver systems. This method is a good candidate (especially for pulsars) , but the small number of stations (10–14) does not measure up to the desired image fidelity which requires 500–1000 stations.

LAR - Large Adaptive Reflector (Canada) Similar to KARST, but uses a much shallower parabola, requiring much greater deformations of the surface and the feed/receiver system to be supported at a height of several kilometres on a tethered ballon. It gains some sensitivity by using more of the surface, but suffers from foreshortening at low elevations. It is unproven technology which is unlikely to be as cheap as the FAST proposal due to greater engineering complexity and offers no clear advantages over the FAST proposal apart from more flexibility in location.

Scaled GMRT technology (India) 9000 12m dishes built using wire rope and cheap Indian labour. A more conventional design, which in some respects could be considered the current pace setter as it satisfies a large fraction of the specifications and the affordability has already been demonstrated in the construction of GMRT which has 30 45m dishes and cost ~ \$500 m^{-2}. The success or otherwise of GMRT in the coming years may have a strong bearing on the future success of this proposal for the SKA.

Commercial 5m Dishes (USA) 50000 5m commercial off the shelf dishes. The idea being to take advantage of the cost savings from using components that are already under mass production. Apart from the construction method of the dishes, this proposal has a lot in common with the Indian proposal. The prototype presently being constructed, the 1hT (1 hectare telescope), should give a good indication of the affordability.

Planar Phased Arrays (Netherlands) This proposal aims to take the concept of riding on components with commercially driven costs a step further, by moving as much as possible of the telescope infrastructure into a technology that not only has high commercial demand, also has a rapidly improving cost curve and future scalability. ie to move away from mechanically based infrastructure to information based technology that presently has an exponential growth curve. The main proposal is to have a flat collecting area and steer the telescope electronically by forming beams in the appropriate direction. A great advantage of this proposal is that it makes it possible to do several experiment simultaniously, by using multiple beams. However it does suffer from foreshortening, and reduced sensitivity, because it cannot have cooled receivers.

Luneberg Lenses (Australia & Russia) While the above proposals have been around for some time, this one is quite recent. People are wrapped with the flexibility and multiple beams of the planar arrays, but frustrated with the poorer sensitivity and complexity of the planar pahsed arrays. Luneberg lenses may provide a way to overcome that. A Luneberg lense is a sphere of dialectirc material which has a radial gradient of refractive index. A plane wave impinging on the sphere is focussed at a point on the other side of the sphere - making it possible to have multiple cooled receivers without enourmous beamforming networks.

3. Future Growth - Multiple Beams

To date the sensitivity of radio telescopes has followed an exponential growth curve. The first and most obvious point about exponential growth is that it cannot be sustained indefinitely. Can we maintain it for sometime into the future ? There are 2 basic ways to stay on this exponential curve: 1) Spend more money which requires bigger and bigger collaborations, 2) Take advantage of technological advances in other areas. Radio astronomy is at the point where it needs to do both 1) and 2) to stay on the curve !

3.1. Extensibility Through Improved Technologies

System Temperature: Reber started out with a 5000 K system temperature. Modern systems now run at around 20 K, meaning that if everything else was kept constant, Reber's telescope would now be 250 times more sensitive than when first built. There are possibilities of some improvements in future, but nothing like what was possible in the past.

Band Width: Telescopes like the GBT (Green Bank Telescope) having bandwidths some 500 times greater than Reber's, will give factors of 20–25 improvement in sensitivity. Some future improvements will be possible, but again they will not be as large as in the past.

Multiple Beams: In the focal or aperture plane, multiple beam systems provide an excellent extensibility path, allowing vastly deeper surveys than were possible in the past. Although multiple beam systems have been used in the past, the full potential of this approach is yet to be exploited. A notable example that has made a stride forward in this direction is the Parkes 13 beam L band system (Stavely-Smith et al. 1996, pASA 13 243). The fully sampled focal plane phased array system being developed at NRAO by Fisher and Bradley highlights the likely path for the future.

The sensitivity of the 64m Parkes telescope for example, has improved by a factor of 400 since 1962. Scope for continuing this evolution looks good for the next decade, but beyond that more collecting area will be needed. Putting a 100 beam system on Arecibo by 2005 is technically feasible and would allow Arecibo to jump out in front of the curve as it did when first built in 1964.

4. Other New Facilities

The aim of this and the following section is to give you a feel for which new radio facilities are likely to be the most useful for pulsar studies. Other spectral bands are covered by other speakers at this meeting, eg Trumper on X-rays. Table 1 summaries the new radio facilities and their likely completion dates. At present, Arecibo and Parkes (with the 13 beam receiver system) are roughly equivelent in terms of their survey capability (rate at which a given area can be searched to a given sensitivity) and are well ahead of the next best facilities and some of the new facilties such as ALMA, GBT, 1hT and VLA. GMRT may join this group, as could GBT or any of the other large single dishes if they opted for multi beam receiver systems.

	D(m)	Area(m^2)	Freq(GHz)	Date
ALMA	64 × 12m	7.2×10^3	30.0 – 900	2007
GBT	1 × 100m	7.8×10^3	0.30 – 86	2000
1hT	512 × 5m	1.0×10^4	1.00 – 12	2003
VLA	27 × 25m	1.3×10^4	0.20 – 50	2002
GMRT	30 × 45m	3.0×10^4	0.03 – 1.5	1999
SKA	????????	1.0×10^6	0.20 – 20	2015
LOFAR	10^6 × 1m	1.0×10^6	0.03 – 0.2	2003

Table 1. New radio astronomy facilities, listed roughly in order of decreasing frequency and increasing area. The VLA specs include the proposed major upgrade.

5. Pulsar Survey Strategies

The SKA is almost certain to be an array with a large number of elements (N). In the past, large area surveys for pulsars at radio wavelengths have been dominated by large single dishes, Molongolo being a notable exception. This is mainly because when an array is used to form coherent beams, the beam size is very small and therefore sky coverage is slow. A much faster alternative (despite the $sqrt(N)$ loss of sensitivity) is to form incoherent sums of the N array outputs, thereby surveying the whole primary beam. However, this requires a detection system (eg a filter bank) for every antenna element, which becomes expensive. For example (see Table 2) a better rate is achieved in a much more cost effective way by putting 13 receivers and detection systems on Parkes, than putting 27 on the VLA ! A particularly striking fact shown in Table 2 is that this may continue to be true even if the SKA is built ! A 100 beam system on Arecibo can find pulsars as fast as a 7 beam system on the SKA ! For a few million dollars Arecibo could be kitted out as the search engine to find all the pulsars, which can then be timed quickly, using the enhanced sensitivity of coherent beams on the full SKA. Forming coherent SKA beams would also be the method of choice for small area searches, for example in globular clusters.

To date, pulsar surveys are both sensitivity and dispersion limited, including the 1.4GHz Parkes multibeam survey. The SKA, LOFAR and a 100 beam Arecibo will remove the sensitivity limitation. LOFAR is unlikely to find vast number of millisecond pulsars because it will continue to be dispersion limited. The SKA and a 100 beam Arecibo can push to GHz frequencies and beat the dispersion, scattering and sky noise limits while still having enough sensitivity. This is in contrast to the common (and incorrect) assumption that pulsars provide a scientific driver for a low frequency SKA.

Telescope	Diameter(m)	Number	Beams	Rate
Present				
ATCA	22	6	1	0.2%
Parkes	64	1	1	0.3%
Jodrell	76	1	1	0.5%
WSRT	25	14	1	0.7%
Effelsberg	100	1	1	0.8%
VLA	25	27	1	1.3%
Parkes	64	1	13	4.2%
Arecibo	300	1	1	7.1%
Future				
ALMA	12	64	1	0.7%
1hT	5	512	1	1.0%
GMRT	45	30	1	4.8%
Parkes	64	1	64	20.7%
Jodrell	76	1	64	29.1%
Effelsberg	100	1	64	50.4%
GBT	100	1	64	50.4%
SKA	5	50768	1	100.0%
Arecibo	300	1	64	453.8%
SKA	5	50768	7	700.0%
Arecibo	300	1	100	710.0%

Table 2. Estimated rate at which a given area of sky can be surveyed for pulsars to a given sensitivity using various exisiting, proposed and potential radio astronomy facilities. The rates are scaled so that 1 beam on the SKA is 100%. The current Parkes multibeam survey (see Camilo et al. from this meeting) with 13 beams provides a benchmark. This table assumes that every telescope has equal bandwidth and system temperature. The Parkes multibeam survey has Tsys $\sim$ 30K and a bandwith of 288 MHz.

6. Timing

Except for a few pulsars, the precision of pulsar timing is presently limited by sensitivity rather than systematics, uncalibrated instrumental effects or unmodelled drifts in the pulsar signal. Sensitivity will no longer be a problem with the SKA and systematics will dominate. Trying to assess what sort of timing precision is achievable is therefore quite difficult, because we cannot characterise the systematics yet or know whether they can be dealt with. Pulsar timing is limited by systematics around 1 μs or a bit below. It therefore seems likely that the SKA would allow a large number (perhaps 100's) of pulsars to be timed to this level of precision. Using 1 beam it might required something like 10 hours to obtain suitable data to time 500 pulsars at the 1 μs level. Using 10 beams that could be randomly positioned, it would take only 1 hour.

Whether the precision can be pushed well below 1 μs remains to be seen. As discussed by Britton at this meeting poor calibration of polarisation is a dominant systematic effect at present and the invariant profile method he proposes should to help solve that problem. However, the SKA is likely to have a planar phased array either in the aperture plane or the focal plane. The polarisation characteristics of these devices are substantially different to anything we are currently use for timing pulsars. It would be advisable for somebody to do some experiments to see how well we can do pulsar timing with such systems. Another question is the number of pulses (normally 100's) needed to form a stable profile for timing. This may limit the speed with which a group of pulsars can be timed with the SKA.

7. Some Other Pulsar Uses

What others things may be possible with the SKA that are not possible now. Of course there will be many that we cannot yet think of, but it does not hurt to mention a few of those that we know now. Simultaneous multi frequency, multi pulsar studies will be a lot easier. The SKA will make it possible to do single pulse studies for a large number of pulsars, compared to the handful at present. One interesting possibility arises if the SKA is made using a planar phased array or Luneberg lens. One could collect signals from every element and store them in a FIFO buffer of say 1 hour in length. In the mean time, collect timing points on pulsars that are likely to glitch. When one sees that a pulsar has glitched, the FIFO buffer should be saved so that a beam can then be formed towards the pulsar and thereby obtain data during the glitch. This idea of course extends beyond pulsars and could be used for detecting any transient source where there is a trigger available by other means.

8. SKA References and Web Resources

Reference	Web Address	Item of Interest
Australia	www.atnf.csiro.au/SKA/	Luneberg Lens
Netherlands	www.nfra.nl/skai/	Planar Array
Canada	www.ras.ucalgary.ca/SKA/	Science Case
SETI	www.seti.org/	1hT
China	159.226.63.50/bao/LT	FAST/KARST
USA	www.usska.org	USA SKA consortium
Backer	www.nfra.nl	1999 Amsterdam SKA meeting
Bailes	www.atnf.csiro.au/SKA/WS/wsmb	1997 Sydney SKA meeting
Fisher	www.nrao.edu.au/~rfisher/	Array Feed