Multiple Widely Spaced Beams for the SKA?

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1 Introduction

The ability to simultaneously place a large number of beams anywhere in π steradians is an exciting and unique possibility with some SKA designs. In particular, it is possible to do this for phased array designs with broad beam elements (van Ardenne, 1998), or Luneburg lenses (James et al. 1999). It is not possible with LAR (Dewdney 1999), FAST (Peng, 1999), GMRT (Swarup, 1997) and 1hT (Dreher, 1999) designs. Cylindrical antennas (James & Parfitt, 1999) allow large separation in one direction only. The science case for multiple widely spaced beams has not been crystallised to date. It is very important to clarify this science case, because if it is very strong, it provides a strong lever on the technology decision. If it is not strong, the planar phased array and Luneburg lens designs will have to compete on other factors common to most designs. We also attempt to clarify some of the details of the multiple beam specification. So far we do not find many individual scientific drivers or experiments requiring widely spaced multiple beams, but this document may provoke you to think of some. We do note that there are tremendous benefits including: the ability to conduct parallel experiments, future extensibility and political funding advantages of a multipurpose facility.

2 Extensibility, Parallel Experiments and their Unique Political Advantages

In past decades radio telescopes have achieved tremendous levels of extensibility, mainly through lower receiver temperatures, increased bandwidth, greater collecting area and longer integration times. More recently, multiple feed or beam systems are being used to increase the sensitivity of surveys and imaging applications. In the SKA context, the major limitation on the number of multiple widely spaced beams is the computational power of the signal processing engines. Moore's law and other predictions indicate that this computational power will continue to grow for some time. This, therefore, provides a natural extensibility for the survey sensitivity of the SKA and the number of simultaneous users. The ability to simultaneously support several very different projects is something that no radio facility has ever had before. In that sense multiple widely spaced beams provide political advantages, because there is both a wider cross section of interested researchers and radical new initiative that is more appealing to funding bodies than asking for money just to build a bigger version of what we already have.

3 Science Goals and SKA Technical Specifications

Table 1 below summarises the scientific drivers that we can think of at present (we do not presume to be able to list them all – we merely aim to provoke your ideas) and what kind of multiple beam requirements they are likely to have. There are many other scientific drivers for the SKA in general (described in the science case (Taylor & Braun 1999)) and we only include here those that appear to have relevant multiple beam requirements.

SKA SPECS AND SCIENCE DRIVERS	Imaging		Point Source Time Variability				Fast Switching	Base Band Buffer	Sub Array
	Widely Spaced	One Degree Patch	Widely Spaced		One Degree Patch	Short Time Scale <1ms			
			Multiple Targets	Multiple Users					
NASA Deep Space Network planet cluster					X				X
NASA Deep Space Network			X	X					X
Galactic X-Ray Binaries		X		X				X	
Geodesy	X		X						
Gravitational Lensing		X							
Transient Events		X		X		X		X	
HI spectral line surveys		X							
Ionosphere		X			X	X			
Masers		X							
Pulsar Timing				X	X	X	X	X	
Pulsars Gravity Wave Detection						X			
Radar Receiver			X		X	X			
Satellite Tracking			X				X		X
SETI			X	X		X		X	
Simultaneous Multi-observatory	X	X		X	X		X		X
Solar System		X			X				
Supernovae		X	X	X			X	X	
VLBI		X		X	X				X

Table1: Summary of possible SKA multiple beam features and some related science drivers.

4 Summary of Technical Specifications

4.1 Widely Spaced or one-degree patch

There are strong scientific drivers (surveys in particular) for multiple beams (up to 100) in a one-degree patch and this has been included in the working specifications. Most of the proposed telescope designs make this possible. However, not all designs can provide multiple beams (10 or 100) that can simultaneously be pointed anywhere within π steradians. A key point on which this document aims to provoke some discussion is what are the scientific drivers for such widely spaced beams, how many are required, with what angular separation, etc. If the scientific case is strong and it becomes a formal specification, then some designs may be ruled out straight away and effort concentrated on the remaining designs.

4.2 Imaging or Point Source Variability

Just as the antenna design limits which part of the sky can be accessed, the back-end processing limits what can be done with the information. One design goal is to image 100 beams within a one-degree patch. For this information to be collected, requires a very large correlator irrespective of the antenna design. Initially the SKA may have the resources for only one such correlator. However, it should be possible to partition the correlator resources between multiple widely space targets that may only require time variability of point sources. There are some experiments (eg pulsars, SETI) for which the signals from the elements only need to be combined to form a single phased array output with reciprocal band width for full sensitivity. Large area surveys for example are likely to be satisfied with multiple beams positioned anywhere within a one-degree patch, while some monitoring applications may require widely spaced beams spread over π steradians. Backend processing for 100 such sources is comparatively cheap when compared to a full one-degree spatial processor. The science drivers for imaging (spatial information) and time variable (temporal) processing are quite different. The cost differences for the two forms of processing, imaging and temporal, means that the science drivers for the two categories need to be closely assessed.

4.3 Multiple targets or multiple users

These subcategories are separated to distinguish between individual experiments which require “multiple targets” to be observed simultaneously and those experiments which benefit greatly from being able to observe in parallel with a completely different experiment – “multiple users”. “Multiple targets” experiments might include things like DSN space craft tracking, or VLBI (where it would be advantageous to observe a target source and phase calibration source simultaneously), or pulsar timing (where you might wish to directly compare the arrival times of pulses from 2 pulsars rather than comparing them via an Earth based clock). The “multiple users” specification would apply to situations where more than one time critical application requires the SKA, each with different frequency band and backend processing requirements. For example, if the SKA was tracking a space craft mission and suddenly an interesting gamma ray burst occurred, widely spaced multiple beams would permit both experiments to occur, rather than having to choose between them.

4.4 Short time scale

This subcategory attempts to identify those experiments that require very high time resolution.

4.5 Fast Switching

If widely spaced beams are not appropriate given the overall science case, or are simply too expensive, some experiments may be possible if there is a fast switching capability, ie the ability to instantaneously or nearly instantaneously move a beam to point anywhere in π steradians. The kind of experiments which require such a capability are any transient events such as SETI, gamma and x-ray bursts, pulsar glitches etc. If there is a strong requirement for this capability, this may also discriminate between the proposed technologies. This is easy to achieve with a planar phased array, and may be possible with Luneburg lenses, but time scales are much longer for most of the other proposed technologies.

4.6 Base band buffer

The proposal here is that base band signal from every element could be recorded in a large base band FIFO of suitable length, possibly 60 – 1000 seconds of data. Then, upon receiving a trigger from a transient event detected by other means, the data in the FIFO could be recorded for later analysis, following beam forming in the direction of the target, once the direction is known with sufficient accuracy. Like the fast switching mode, this is possible for those designs that can view π steradians and therefore may also help to discriminate between technologies if there is a strong requirement for it. Another interesting aspect of such a buffer is that all the non-time-variable spatial information within the field of view is recorded. So one could imagine an approach where such a data set was obtained and astronomers would then apply for computer time to form the beam in the direction of interest and make images. By obtaining a shallow all sky survey in this way, the resulting interesting objects could then be followed with high sensitivity. This approach lends itself to an interesting interference mitigation scheme: **Just turn everything off for an hour!** The data recording requirements for this are enormous, ~100 GB per second per MHz of bandwidth per bit of dynamic range per square kilometre of collecting area at a 1MHz centre frequency. The recording rate scales as the centre frequency squared, due to the increased number of elements. This kind of approach is therefore most likely to be possible for a low frequency system like LOFAR (Bregman, 1999).

4.7 Sub array Solution

There is a range of experiments which, while they may require multiple beams (either widely spaced or in a one-degree patch), do not necessarily require the full sensitivity of the SKA. This then opens up the possibility of providing simultaneous multiple beams by splitting up the array into several parts (sub arrays) in a fairly dynamic fashion. It does require some extra infrastructure and suffers sqrt(N) loss in sensitivity. A big advantage is that this can be achieved for most, if not all, of the proposed designs.

5 Summary of Science Goals

The NASA **Deep Space Network** (DSN is becoming data rate limited and this will only get worse in future (Kuiper, 1999)). Many of the DSN systems are moving to high frequencies to reduce this problem. The SKA could provide the required data rates (because of the huge collecting area) and excellent flexibility using multiple widely spaced beams would allow simultaneous tracking of many space craft. As well as a general increase in the number of space craft, there is also a move to cluster based missions, with many spacecraft around a planet.

Transient Events include events such gamma-ray bursts, X-ray Binaries, pulsar glitches. While for some events there is a considerable delay in the appearance of radio emission, there are other cases which would benefit immensely if observations could be obtained at the time of the event using a base band buffer or fast switching approach.

Geodesy is the study of time and motion on Earth. It uses high resolution observations of extragalactic radio sources which form a fixed reference frame. Presently it is limited by the ability to correct for atmospheric and ionospheric effects, as well as clock synchronisation and drift and Earth rotation and polar motion. Widely spaced multiple beams would provide the possibility of simultaneously phase referencing all the extragalactic reference sources and thereby improve the above correction and accuracy geodesic solutions by at least an order of magnitude.

Both strong and weak **Gravitational Lensing** experiments are likely to be carried out using the SKA. Much wider fields of view (e.g., size of Abell clusters) are required for the weak lensing experiments. It seems likely that a one-degree field of view at ~1400 MHz would be sufficient.

Studying the formation of galaxies by observing the **HI** profiles is a key science driver for the SKA. The two likely aspects of this project are wide area surveys and detailed studies of individual clusters and galaxies at high spatial and frequency resolution. The vast majority of this science seems to be achievable with many beams spread over a one-degree patch.

The requirements for application of the SKA to **Maser** studies are rather similar to the HI requirements.

The SKA would be an ideal receiving station for studies of plasma wave phenomena in the **Ionosphere,** which result from injecting radio and microwave signals. Widely spaced multiple beams would allow large parts of the ionosphere to be studied simultaneously.

5 Summary of Science Goals (continued)

An interesting proposal that has been under consideration for some time is the use of an array of radio **pulsars as a gravity wave detector**. To do this you would need to monitor many millisecond pulsar in order to detect the systematic drift introduced into the pulse arrival times by a passing gravity wave that causes the Earth or the pulsars to wobble relative to each other. The low frequency of gravity waves for which this method fills a niche (LIGO, LISA and other like experiments have much more sensitivity to high frequency gravity waves) does not require parallel observation of many sources, but fast switching would be very beneficial.

Pulsar Timing would benefit from widely spaced multiple beams. From a telescope resource allocation point of view it is much harder to maintain a useful timing program than it is to conduct a survey to find pulsars (especially if the survey takes advantage of multiple beams within a one-degree patch).

The operation of the SKA as a **Radar Receiver** would benefit greatly from parallel observations and from the ability to receive bounced signals from many directions simultaneously for radar ranging experiments.

Satellite Tracking - The task of regularly redetermining accurate satellite orbital elements would require parallel observations of many sources – potential money earner or partner in construction.

SETI – The Search for Extra Terrestrial Intelligence. The key question for SETI experiments in this context is whether enough targets can be found within the one-degree patch. If so, widely spaced multiple beams are not required.

Simultaneous observations with multiple facilities are often very difficult to schedule, requiring other programs to be moved around. Being able to steer a beam in the appropriate direction when other facilities were “online" would make a huge difference.

5 Summary of Science Goals (continued)

All of the bodies in the **solar system** are one degree or less in size. Unless there are applications that require simultaneous studies of two or more bodies, or wide area studies of the interplanetary medium, a one-degree patch would be sufficient.
Like pulsars, one of the key applications of **Supernovae** studies is long term monitoring. Since there will be so many that need monitoring, it will be very important to be able do this in parallel with other experiments.
VLBI would greatly benefit from parallel observation of reference and target sources. VLBI is so time consuming (ie requires earth rotation) the usefulness of this technique would be greatly enhanced by parallel observations. A key point is that the space based station cost is comparable to the cost of the SKA. Providing a beam to do continuous VLBI maximises the utility of the investment in the space stations. Other vital aspects include providing a beam to solve the phase reference challenge and another to down link the data from the space station, so that the correlations and maps can be formed in near real time.

6 Makin' movies

One of the most stringent requirements would arise for those experiments which may require high time resolution images. A question to be addressed is what is the maximum time resolution possible for a given number of elements, and when is it feasible to build a correlator to handle this amount of data? For example, with the excellent image fidelity (uv coverage) available with 500 or 1000 elements, it would be possible in principle to make a movie of a 0.5 mJy (@ 8 GHz) source with a time resolution of 1ms and a spatial resolution of 0.1 arc seconds! This is completely new and unexplored territory for radio astronomy. It would probably be sufficient to do this just for a single beam. With a sufficiently flexible backend, the same signal processing resources required for multiple beams could be applied to this high-time resolution imaging mode. If the correlator is not powerful enough to handle this, it may still be possible to do some useful experiments, by buffering the data and then allowing it to trickle slowly through the correlator. This could be the same buffering system as the one required for the base band buffer.

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