

Multibeaming Discussion at Groningen

Jim Cordes & Russ Taylor

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The discussion centered on the the following questions:

- (a) What is meant by multibeaming in the context of the SKA?
- (b) What science areas need multibeaming to achieve the Level 1 science areas? Here we distinguish between multibeaming as an enabling feature and multibeaming as a capability that increases the efficiency of observations.
- (c) If multibeaming is required, is the full SKA needed for each beam? and
- (c) What response time(s) are needed in beam forming to respond to a trigger from (e.g.) another instrument?

I. Basic Definitions: To discuss multibeaming as clearly as possible, we first define some basic terms.

Primary Beam = response of an individual element at a single focal point.

At L band we have for the various designs the following primary beam diameters:

$\ll 1$ deg	KARST, LAR
~ 1 deg	Australia, India, USA
$\gg 1$ deg	Europe

In the KARST and LAR designs, feeds at multiple focal points are used to produce multiple primary beams on the sky and thus meet the specification of 1 deg FOV at 1.4 GHz. All other designs meet the specification with single feeds, though they too could utilize multiple feeds.

We also need to define several beams associated with arrays of primary elements:

Station Beam = the synthesized beam of a *station* built up from primary elements. (For single-dish stations such as the KARST and LAR this is identical to the Primary Beam.)

Core-Array Beam = the synthesized beam from elements within a central core array.

Science areas that need a core-array beam include those requiring high surface brightness sensitivity at intermediate angular resolution (EoR studies, HI detection of galaxies, molecular line studies), and blind surveys for pulsars, transients and SETI.

It is useful to define the core-array beam because elements within the core-array can be phased together or correlated individually. In this sense, the core-array is simply a large station. Additionally, and perhaps most importantly, it may be possible to sample the *entire* FOV of ~ 1 deg at 1.4 GHz only for the core array. The size of the core array is TBD and is dependent on details of the science case. However, it should be noted that if the SKA FOV specification ~ 1 deg (see below) is to be sampled completely, the requisite number of core-array beams $\propto b_{\text{core}}^2$, where b_{core} is the diameter of the core array. For time-domain science and spectroscopy, the number of operations scales with the number of core-array beams. For these areas of science, the core array should be as small as possible (e.g. $\lesssim 1$ km). However, imaging of low-surface brightness structures (EoR and Galactic non-thermal radiation, for example) might push the core-array to larger sizes, e.g. up to 10 km.

SKA Beam = synthesized beam of the entire SKA.

Finally, we define the field of view (FOV) in terms of previous definitions and relate it to the current SKA specification:

Single-focus FOV = the primary beam \times delay beam (or equivalent), where the relevant delay beam is for a station composed of multiple elements. For the KARST and LAR designs, the single-focus FOV is identical to the primary beam. For the European tile design, the delay beam is presumably much smaller than the primary beam.

FOV = the *aggregate* FOV including any multiple focal-plane sampling (KARST and LAR).

The SKA specification is for FOV ~ 1 deg at 1 GHz. For the European tile design, the FOV specification is much smaller than the intrinsic beam width of the tiles. Multibeaming is therefore much more flexible in this design and it is possible to simultaneously sample regions of the sky separated by $\gg 1$ deg and using the entire collecting area of the SKA. The Australian cylindrical design allows such sampling in one dimension, while all the remaining designs require a sacrifice in collecting area if $\gg 1$ degree sampling is used.

II. What is Multibeaming? Two definitions are used in discussions about the SKA:

Definition 1: Multibeaming = multiple beams formed within the FOV. If formed in real time these would result from a beam-forming system; if formed off-line, we would call these synthesized beams.¹ We prefer this definition of multibeaming.

Definition 2: Multibeaming = multiple, simultaneous fields of view (FOV) spaced widely on the sky. This kind of multibeaming requires a sacrifice in sensitivity in the KARST, LAR, US and Indian designs. For the European tile design and the Australian cylinder and lens designs, multiple FOV can be achieved through multiple feeds (or equivalent focal-plane sampling).

The strawman specifications indicate a requirement of 100 beams that conform to Definition 1. Some science discussions, however, imply the need for multibeaming according to Definition 2. *We recommend that Definition 1 be used for ‘multibeaming’ while Definition 2 can be referred to as ‘multiple fields of view.’*

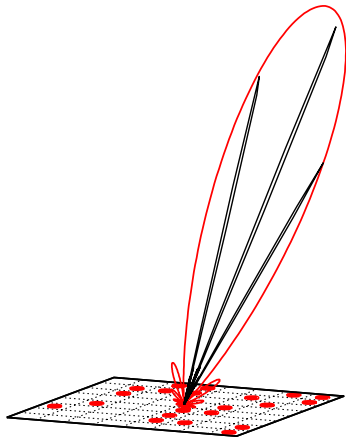


Fig. 1.— **Multibeaming Definition 1:** Depiction of a station, the primary beam of an array element (red), and multiple array beams (black) within the primary beam. These array beams are called *synthesized beams* in off-line analysis and would be the outputs of a real-time *beam former* if formed in real time. For the European tile design, the primary beam $\gg 1$ deg while for the KARST

¹In the following we will refer to array beams as synthesized beams, for simplicity, independent of how or at what time they are implemented.

and LAR designs, the primary beam $\ll 1$ deg. The remaining (Australian, Indian, and US) designs all have primary beams ~ 1 deg, at least in one dimension.

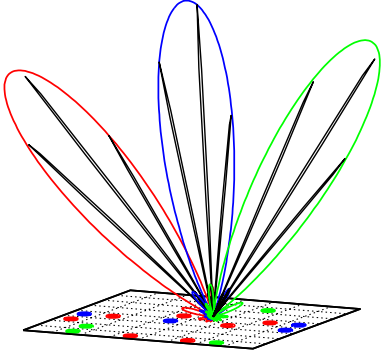


Fig. 2.— **Multibeaming Definition 2:** Here multiple primary beams (red, blue, and green) are shown that correspond to usage of subarrays of station elements. Within each primary beam, multiple array beams are formed (black).

III. What are the scientific needs for multibeaming? And with what gain and response time? Comments from the scientific Working Groups of ISAC are as follows:

WG1 *Galactic HI, Nonthermal Emission and Magnetic Fields:*

Multibeaming is not critical but maximizing FOV is important.

WG2 *Transients, Stellar end products, and SETI:*

Multiple beaming (Definition 1) is needed to the extreme where the entire FOV is ‘accessible’ in the time-domain and spectral-line studies that comprise the science of this WG.

Blind surveys for natural or artificial signals require construction of time series from all beams needed to cover the FOV. Such time series need to have time resolutions $\lesssim 100 \mu s$ and with spectral resolution ~ 0.1 MHz for pulsar and transient surveys, ~ 10 kHz for spectral line surveys (natural sources), and

$\lesssim 1$ Hz for SETI. (These data sets might more naturally be referred to as dynamic spectra.)

The data rate associated with this requirement scales with the square of the maximum baseline on which full-FOV beam forming is done. Realistically, full-FOV analysis can be done only on the core-array. If the maximum baseline is b_{core} , then the number of beams needed is $N_{\text{beams}} \sim \Omega_{\text{FOV}} b_{\text{core}}^2 / \lambda^2$. Unless the core-array is smaller than a few km, the implied data rate ($\sim N_{\text{channels}} N_{\text{beams}} / \Delta t$, where N_{channels} = number of spectral channels and Δt = sample interval) is most likely unachievable.

The size of the core-array needed for WG 2 science needs to be considered in more detail, especially in relation to data rates and to other areas of science that require a core array. This also raises the question, “What fraction of A_e should be in a core array?” We note that WG 2 also requires the SKA to have collecting area on long (‘VLBI’) baselines for astrometric purposes and for studies of interstellar scattering.

Caveat and Comment: For blind surveys that require sky coverage much larger than the specification $\text{FOV} \sim 1$ deg (at 1.4 GHz), sensitivity (A_e / T_{sys}) may be sacrificed. That is, we can use multiple fields of view (Definition 2) by sub-arraying the SKA. This follows because, except for pulsar surveys, we do not know the sensitivity requirements for the transient sky nor for ETI sources. Additionally, for much of this WG’s science, the collecting area can be used in a mode where widely-spaced stations or collections of stations are used for anticoincidence tests of RFI.

Targetted Searches and Observations , e.g., SETI on individual stars, pulsar timing, radio studies of X-ray selected objects, need “many” multiple beams within the FOV. This yields a large increase in efficiency that implies a qualitative change in how the science is conducted. The technical requirements (number of beams, data rates) are less stringent than for blind surveys.

Response Times: Triggers may be expected from the SKA itself or from other telescopes throughout the electromagnetic spectrum (and perhaps from non-electromagnetic facilities: gravitational wave and neutrino detectors). For gamma-ray bursts, for example, response times of seconds are needed to determine whether there is a prompt radio burst in addition to the well-known afterglows. Dispersion delays ($\propto \text{frequency}^{-2}$) in interstellar and intergalactic media can aid in lengthening the response time needed, especially at low frequencies. The rate of radio bursts is not known so we cannot specify what FOV is needed to yield SKA self-triggers at a rate, say, of one per day. If we use the detected GRB rate $\sim 1 \text{ day}^{-1}$ in a hemisphere, then the nominal FOV ~ 1 deg will yield a very small rate $\sim 10^{-4.3} \text{ day}^{-1}$.

Triggers from other instruments, such as gamma-ray satellites, are likely to require tens of seconds.

Two related issues are:

1. Requirements on phasing of the SKA using celestial sources. How often will this be needed and over what solid angle will the phasing solution be valid?
2. What are the requirements on a ‘delay buffer’ that would allow transients to be identified after the fact. Is it feasible to use such a buffer only with the core array? Or with a few stations? What are the costs as a function of sampled solid angle?

WG3 *Cosmology and Large-scale Structure:*

Multibeaming is not critical but maximizing FOV enhances the science

WG4 *Galaxy Evolution:*

Multibeaming not essential.

WG5 *AGNs:*

Astrometry (phase referencing) and calibration greatly benefit from having four beams (sufficient to solve for a plane-slab atmosphere).

Source slewing times need to be small to allow monitoring of many sources, including Intra-Day Variable (IDV) sources which sample the changing interstellar medium. What is small? During the Groningen discussion “10 sec or less” was stated. However, it is not clear that such fast response results from Level 1 science requirements. For example, with the great sensitivity of the SKA, fainter and more compact sources can be detected that will show IDV. The density on the sky of IDV sources will be sufficiently large that an IDV source can be found relatively near to any arbitrary position. IDV time scales are typically an hour or more, so slewing to a particular source does not seem to require a very rapid slew rate.

WG6 *Life Cycles of Stars:*

Multibeaming not essential.

WG7 *Solar System:*

No comments given.

WG8 *Intergalactic Medium:*

No comments.

WG9 *Spacecraft Tracking and Geodesy:*

Wide-angle multiple FOVs (c.f. Definition 2) are useful for space-craft tracking but not a fundamental requirement. The full gain of the SKA may not be needed for this; sub-arraying may be sufficient.

Time multiplexing is not useful for telemetry reception.

III. Questions for Further Study

1. What is the maximum data rate that can be achieved in 10 to 15 years, taking into account the beam-forming process, large numbers of channels, and high time resolution needed for WG 2 science? What parts of the required processing are real-time and which off-line?
2. What fraction of the SKA's collecting area should be in a core array and how large should this core array be? This is equivalent to the question, "Over what subarray size can we instantaneously sample the entire FOV ~ 1 deg for time-domain studies and spectroscopy?"
3. What are the specific needs for fast response times?

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