Imaging with the SKA: Comparison to other future major instruments

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1 Introduction

The Square Kilometer Array is going to become operational at the time when several new large optical (LBT, CELT, EURO50, OWL) X–ray (CONSTELLATION-X, XEUS, MAXIM) and Gamma–ray (GLAST) telescopes are expected to be working. The main drive for building the SKA is a significant improvement of sensitivity that would widen the general scope of the centimeter–wavelength radio science and connect better the radio science with astrophysical studies made in other bands of electromagnetic spectrum. To this end, a thorough designs studies should be made, in order to ensure that the SKA becomes a competitive counterpart to the large optical and X–ray instruments which would be built in the next several decades. In the past two decades, radio astronomical instruments have typically featured a superior resolution and adequate imaging performance, compared to the instruments working in other spectral bands. The future optical telescopes like CELT and OWL would both surpass the dynamic range offered by the VLA and match the resolution of ground–based centimeter wavelength VLBI. This is a compelling argument for designing the SKA such that it offers similar imaging capabilities. A brief discussion of some of the SKA designs is presented here, with special attention paid to spatial dynamic range offered by those designs.

2 Imaging performance of the SKA

Imaging performance of different SKA designs is compared in Table 1 for five out of seven basic concepts currently being considered (the Indian and the Chinese designs are omitted). The technical parameters are taken from the draft designs collected on the "System definition" page for the SKA at the ATNF. The parameters in Table 1 are designated as follows: ν – observing frequency; B – baseline; D_{an} – equivalent diameter of a single array element; T_{sys} – system temperature at 1.4 GHz; A/T_{sys} – aperture/system temperature ratio; SEFD – system equivalent flux density; N_{an} – total number of array elements; N_{st} – total number of array stations; $\Delta u/u$ – Fourier plane filling factor of the array; $\mathrm{SDR}_{\mathrm{FOV}}$ – theoretical spatial dynamic range, unconstrained by the array design; ΔI_{m} – point source sensitivity (with $\Delta t = 1$ hour and $\mathrm{BW} = 1$ MHz); $\mathrm{SDR}_{\mathrm{m}}$ – spatial dynamic range of observations reaching ΔI_{m}; SDR_{uv} – spatial dynamic range limited by the uv–coverage of the array; BW_{uv} – maximum channel bandwidth required by SDR_{uv}; τ_{uv} – maximum correlator integration time required by SDR_{uv}; ΔI_{uv} – point source sensitivity reached with SDR_{uv}.

The imaging performance can be evaluated by comparing spatial dynamic ranges (SDR) and resolutions provided by the designs. The resolutions of the SKA designs are compared in Figure 1 with the resolutions of various existing and future telescopes. The SDR of the different SKA designs are presented in Figure 2 and compared in Figure 3 with the SDR of other instruments. The SDR are affected by the observing bandwidth, averaging time and filling factor of the Fourier domain, $\Delta u/u$. The effect of the latter parameter is exemplified by Figure 4 in which a simulated image is produced for the scenario of "compact SKA with a few long–baseline outliers".

3 Resolution

All of the basic SKA designs are now enlisting longest baselines of $\gtrsim 3000$ kilometers (Figure 1), which results, for most of them, in an $\approx$1 milliarcsecond resolution at the highest observing frequency. This resolution is going to provide an adequate counterpart to the resolution of the largest projected optical telescopes, and may be inferior to the resolution of the proposed X–ray interferometer mission MAXIM.

Table 1: SKA designs: Imaging performance

Parameter	**Australia Cylinders**	**Australia Lenses**	**Europe Tiles**	**Canada LAR**	**USA SAR**
Frequency and baseline coverage					
$\nu_{\rm low}$[GHz]	0.1	0.1	0.15	0.1	0.15
$\nu_{\rm high}$[GHz]	9.0	5.0	1.5	22	34
$B_{\rm short}$[km]	0.3	0.3	0.5	0.5	0.1
$B_{\rm long}$[km]	10000	3000	4000	3000	3000
Characteristics of a single array element					
$D_{\rm an}$[m]	13	7.0	1.0	200	12
$T_{\rm sys}$[K]	50	40	40	40	30
$A/T_{\rm sys}$[m^2/K]	2.0E+4	2.5E+4	2.5E+4	2.5E+4	3.3E+4
SEFD[Jy]	20.3	81.1	27.0	16.2	32.4
Configuration and *uv*–coverage					
$N_{\rm an}$	600	52800	1.0E+6	60	4400
$N_{\rm st}$	60	300	100	60	160
$(\Delta u/u)_{\rm best}$	0.04	0.06	0.10	0.50	0.17
$(\Delta u/u)_{\rm worst}$	0.11	0.14	0.33	0.50	0.24
Spatial dynamic range and image sensitivity					
SDR$_{\rm FOV}$	1.9E+06	4.3E+05	2.9E+05	1.3E+05	2.2E+05
$\Delta I_{\rm m}$[μJy]	5.7	4.5	4.5	4.5	3.4
SDR$_{\rm m}$	1.1E+04	5.6E+03	1.7E+03	1.1E+04	1.1E+04
SDR$_{uv}$	1.9E+06	4.1E+05	1.8E+05	5.4E+04	1.7E+05
BW$_{uv}$[Hz]	830	280	940	2050	980
τ_{uv}[ms]	83	28	63	207	66
ΔI_{uv}[μJy]	197.5	271.7	147.5	100.4	108.2

The imaging capability of MAXIM is however rather modest ($D \lesssim 700$), and it should be matched easily by radio observations using millimeter– or space–VLBI. For the optical telescopes, the SKA would be able to present a reasonable match, provided that the longest baseline limit is not pushed below 3000 km. Thus, the SKA design that would match well the resolution of the large future optical telescopes, and provide thereby a good opportunity for joint radio–optical studies, must provide roughly a $\lesssim 1$ mas resolution at its highest observing frequency.

A detailed comparison of the SKA designs and various other telescopes can be found at `http://www.mpifr-bonn.mpg.de/staff/alobanov/ska/telescopes.html`

4 Spatial dynamic range

The maximum achievable spatial dynamic range (SDR$_{\rm FOV}$) is simply a ratio between the field of view (FOV) and the synthesized beam (HPBW). For an array composed of parabolic antennas,

$$\mathrm{SDR}_{\rm FOV} \approx 0.80 \frac{B_{\rm long}}{\eta_{\rm a}^{0.5} D_{\rm an}}\,, \qquad (1)$$

where $\eta_{\rm a}$ is the aperture efficiency. However, SDR$_{\rm FOV}$ can be typically achieved only at the shortest baselines. The SDR is significantly reduced at the highest instrumental resolution, due to finite bandwidth ($\Delta\nu$) and integration time (τ) and incomplete Fourier domain sampling. This reduction is visible in all of the SKA designs in Figure 2 (BW=1 MHz and τ=1 s are assumed in these calculations). The maximum SDR that can be achieved at a given integration time is

$$\mathrm{SDR}_{\tau} \approx 1.13 \cdot 10^4 \tau^{-1}\,. \qquad (2)$$

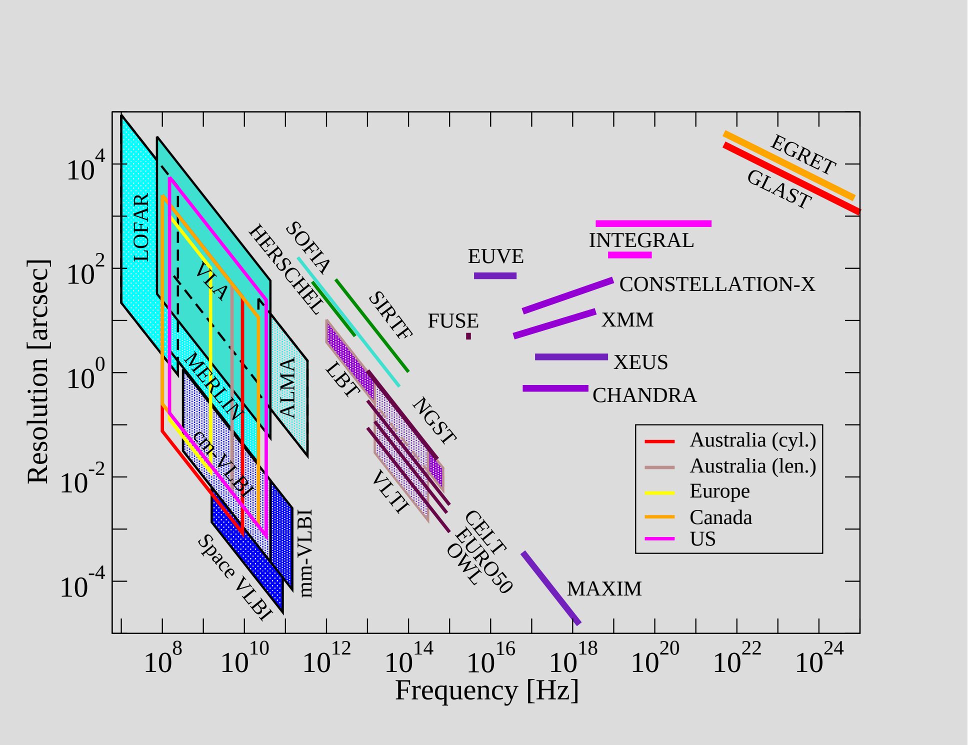

Figure 1: Resolution of the SKA compared with the resolution of other main existing and future astronomical instruments

The finite $\Delta\nu$ yields

$$\mathrm{SDR}_{\Delta\nu} = \frac{1}{\Delta\nu}\left[\left(\frac{I_0}{I}\right)^2 - 1\right]^{0.5}, \tag{3}$$

where I_0/I is the maximum acceptable peak brightness reduction (assumed to be 30%, in these calculations). Incomplete sampling of the Fourier space results in

$$\mathrm{SDR}_{uv} = 3\mathrm{SDR}_{\mathrm{FOV}}\left\{\exp\left[\frac{\pi^2}{16\ln 2}\left(1+\frac{\Delta u}{u}\right)^2\right]\right\}^{-1}. \tag{4}$$

For a regular array (i.e. logarithmic spiral) with N stations, $\Delta u/u$ can be roughly estimated by $(B_{\mathrm{max}}/B_{\mathrm{min}})^{3/N} - 1$. In case of multifrequency synthesis, $\Delta u/u$ should be substituted by $\Delta u/u + \Delta\nu_{\mathrm{mfs}}$, where $\Delta\nu_{\mathrm{mfs}}$ is the fractional bandwidth over which the multifrequency synthesis is performed.

In a real observation, the actual spatial dynamic range is determined by the most conservative of the estimates provided above (this limit is given by $\mathrm{SDR}_{\mathrm{m}}$ in Table 1, for the highest instrumental resolution). For most of the SKA designs plotted in Figure 2, this results in a factor of ∼100 reduction of the SDR at the highest instrumental resolution (the Canadian design suffers from the SDR reduction at all resolutions, due to the small number of stations and poor $\Delta u/u$ ratio). Removing the discrepancy between $\mathrm{SDR}_{\mathrm{FOV}}$ and $\mathrm{SDR}_{\mathrm{m}}$ requires reducing $\Delta\nu$ and/or τ. The reductions necessary to achieve SDR_{uv} are given in Table 1 by BW_{uv} and τ_{uv}. This, correspondingly, leads to an increased point source sensitivity and longer observing time required.

5 Spatial dynamic range in the SKA era

The typical $\mathrm{SDR}_{\mathrm{m}}$ of the SKA will be higher than that of most of the existing astronomical instruments. However, future major optical instruments (see Figure 3) will be able to achieve much higher SDR levels,

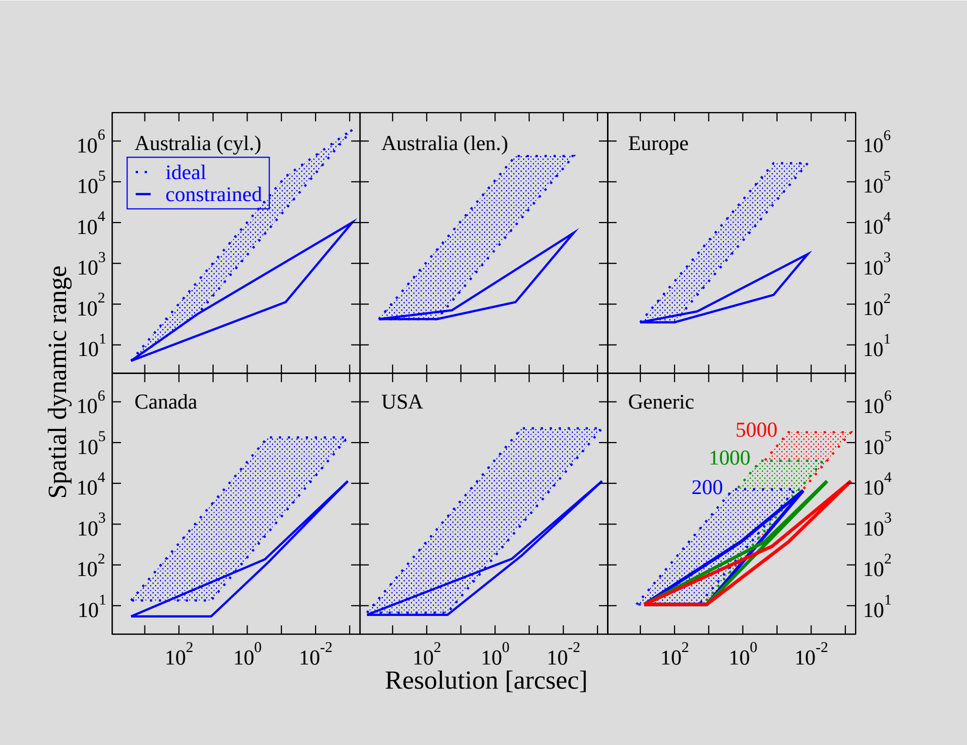

Figure 2: Maximum (shaded areas) and realistic (solid polygons) spatial dynamic ranges of different SKA designs plotted against the resolution (the panel with "generic" designs describes a "typical" SKA with baselines extended up to 200, 1000 and 5000 km, respectively).

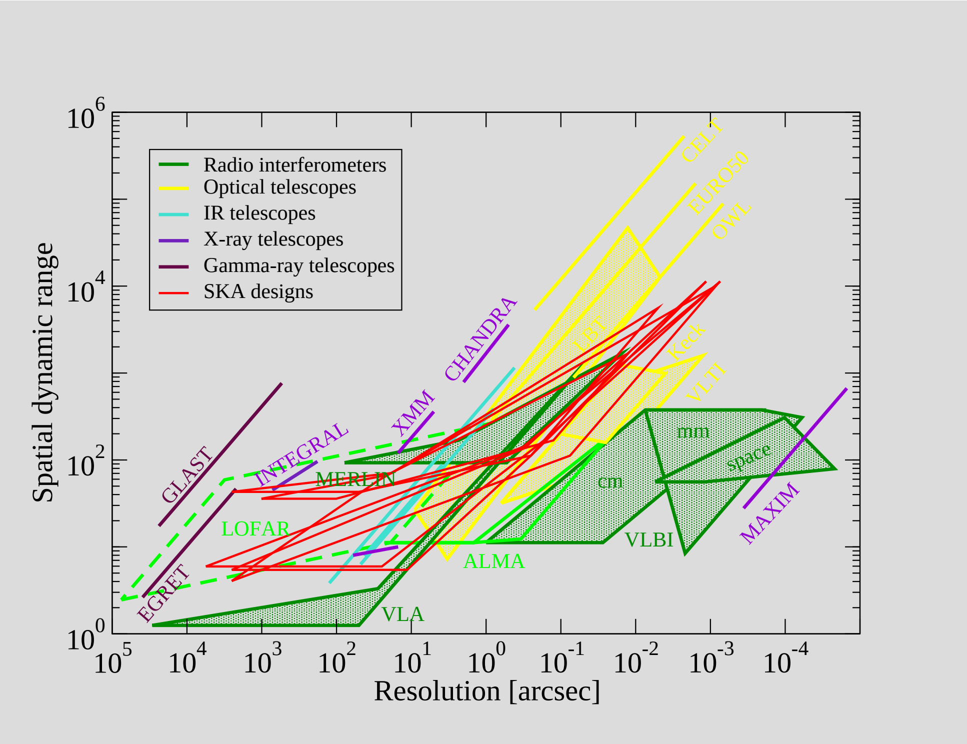

Figure 3: Spatial dynamic range of the SKA designs ($\mathrm{SDR_m}$ for observations with $\Delta\nu$=1 MHz and τ=1 s) compared to other major instruments.

comparable with the maximum $\mathrm{SDR_{FOV}}$ of the SKA presented in Figure 2. This implies that the SDR reductions described by equations (2)–(4) should be considered carefully at the stage of the instrument design, in order to optimize the imaging performance of the SKA.

For most of the high–dynamic range observations with the SKA the bandwidth and integration time may have to be significantly reduced, if one would require to reach SDR similar to that of the largest optical instruments. These two corrections can be introduced at the stage of observation preparation, and their worst effect is the increased observing time needed to reach the required sensitivity. The Fourier space sampling, described by the $\Delta u/u$ ratio, is however "hard–wired" into the array design, and can only be improved by adding new stations. It is therefore rather imperative to optimize this parameter at the earliest possibles stages of the array design. In addition to that, optimization of $\Delta u/u$ is also required by high–fidelity imaging at low SNR levels. The lowest SNR of "trustable" pixel in an interferometric image is given by

$$\ln(\mathrm{SNR_{low}}) = \left[\frac{\pi}{4}\left(\frac{\Delta \mathrm{u}}{\mathrm{u}} + 1\right)\right]^2 \frac{1}{\ln 2}\,. \tag{5}$$

The SDR reduction due to poor Fourier space sampling becomes significant at $\Delta u/u \gtrsim 0.4$ (see Figure 2). At $\Delta u/u \lesssim 0.25$, the SDR reduction due to the Fourier space sampling becomes negligible. It should therefore be possible to reach the $\mathrm{SDR_{FOV}}$ levels in an array configuration that provides $\Delta u/u = 0.2$ at all baselines. If multifrequency synthesis is applied routinely, this condition may be modified so that $\Delta u/u = 0.2 + \Delta\nu_{\mathrm{mfs}}$. For an inhomogeneous array, in which $\Delta u/u$ varies, the reduction of spatial and even conventional dynamic range may be substantial (see Figure 4). Therefore, the requirement $\Delta u/u \approx \mathit{const} \lesssim 0.2$ must be considered as one of the basic requirements for the design of the SKA.

6 Conclusions

To make the SKA a competitive imaging instrument that would match the capabilities of future optical and X-ray telescopes, two basic conditions must be fulfilled:

1. Resolution of $\lesssim 1\,\mathrm{mas}$ at ν_{high}.
2. Fourier plane filling factor $\Delta u/u \lesssim 0.2$ over the entire range of uv–coverage.

Compromising either of these two conditions would reduce the imaging capability and narrow the scientific scope of the SKA.

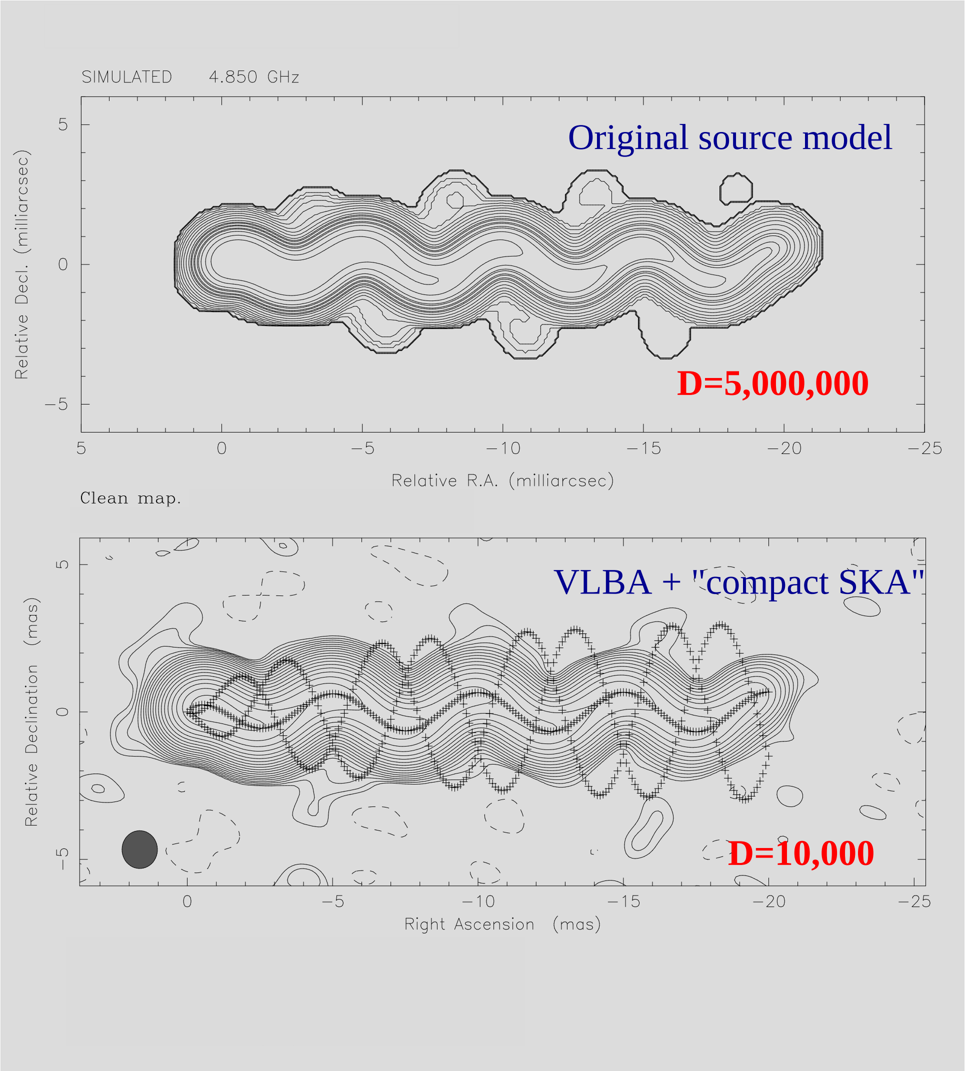

Figure 4: The effect of unoptimized $\Delta u/u$ on image quality. The top panel shows an artificial source model designed with a dynamic range of $5 \cdot 10^6$. The bottom panel is an image that would be obtained with a "compact SKA" (most of the collected area is within 100 km) combined with 10 "outlier" stations at distances of up to 8000 km. The resulting $\Delta u/u$ is $\lesssim 10^{-3}$ for very short baselines and can be as large as 0.5 for the longest baselines. This disparity of $\Delta u/u$ causes a reduction of dynamic range by a factor of 500, as shown in the bottom panel.